PROCEEDINGS
THE INSTITUTION OF CIVIL ENGINEERS

PART I
SEPTEMBER 1955

ORDINARY MEETING

15 March, 1955

DAVID MOWAT WATSON, B.Sc., President, in the Chair

The Council reported that they had recently transferred to the class of

Members

- Ackroyd, John, B.Sc. (*Bristol*).
- Broadbent, Beaumont Holiday, B.Sc. (Eng.) (*London*).
- Edington, George Adam.
- Elliott, Thomas Walker, B.Sc. (*Glasgow*).
- Goode, Alfred, B.Sc. (*Birmingham*).
- Herbert, *W.-Cdr* Frank, *O.B.E.*, B.Sc. (*Manchester*).
- Lampert, Daniel, B.Sc.(Eng.) (*London*).
- Loveridge, Charles Edward, *C.B.E.*, B.Sc.(Eng.) (*London*).
- McFadyean, William Donald, B.Sc. (Eng.) (*London*).
- Mason, Peter, B.Sc.(Eng.) (*London*).
- Ogden, Philip Henry, B.Sc.Tech. (*Manchester*).
- Sparkes, Stanley Robert, M.Sc. (*Bristol*), Ph.D. (*London*).
- Spencer, Kelvin Tallent, *C.B.E.*, *M.C.*, B.Sc.(Eng.) (*London*).
- Tate, William Kenneth, M.A. (*Cantab.*).

and had admitted as

Graduates

- Ashcroft, John, Stud.I.C.E.
- Bailey, Gordon Leonard, Stud.I.C.E.
- Barlow, Dennis Lancashire, B.Sc. Tech. (*Manchester*).
- Barrie, Douglas Keay, B.Sc. (*St. Andrews*).
- Beck, John Aitchison, B.E. (*New Zealand*).
- Blood, John Douglas, Stud.I.C.E.
- Bolton, Kenneth Charles, B.Sc.(Eng.) (*London*), Stud.I.C.E.
- Bratchell, Gerald Ernest, B.Sc. (Eng.) (*London*), Stud.I.C.E.
- Caldwell, John Alan, Stud.I.C.E.
- Campbell, Derek Roy, Stud.I.C.E.
- Candy, Colin Frank, B.E. (*New Zealand*).
- Carr, Isaac Francis, B.Sc. (*Bristol*).
- Casey, Thomas, B.E. (*National*).
- Clifford, Paul Anthony, B.Sc.(Eng.) (*London*), Stud.I.C.E.
- Coath, William Enrique Dans, Stud. I.C.E.
- Collier, Richard Tregonwell, B.A. (*Cantab.*).
- Cumberworth, Ian Ronald, Stud.I.C.E.

Cunningham, Peter Ramage, B.Sc. Tech. (*Manchester*), Stud.I.C.E.
Daniel, David Joseph, Stud.I.C.E.
Denning, Hugh Gordon Vere, B.Sc. (Eng.) (*London*).
Duncan, John Alastair, B.Sc. (*Belfast*).
du Toit, Jocelyn Francois Smuts, B.Sc. (*Cape Town*).
Eddison, John Michael, B.Sc. (*Aberdeen*), Stud.I.C.E.
Fallon, Michael John, B.E. (*National*).
Farrington, Peter, Stud.I.C.E.
Fishwick, Geoffrey, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Gardiner, Douglas Wyper, B.Sc. (*Glasgow*), Stud.I.C.E.
Glanville, John Irvine, B.Sc. (*Belfast*), Stud.I.C.E.
Granger, Raymond Newell, B.Sc. (Eng.) (*London*).
Green, James David Wailes, B.Sc. (*Birmingham*), Stud.I.C.E.
Green, Peter Royston, B.Sc.Tech. (*Manchester*).
Griffith, Kenneth John, B.E. (*New South Wales*), Stud.I.C.E.
Gunawardane, Goluhewage Jinadasa Poujitha, B.Sc.(Eng.) (*London*).
Hansford, Roger Robert Reeves.
Hanson, Brian, B.Sc.(Eng.) (*London*).
Hardwick, Frank, B.Sc.(Eng.) (*London*).
Hart, Archibald Daniel, Stud.I.C.E.
Hayman, Michael John, B.E. (*New Zealand*).
Hayman-Joyce, John Gerald, B.A. (*Cantab.*).
Holman, Donald Harry.
Holmes-Evans, Thomas Walter, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Hutton, John Neville Mounsey.
Irvine, Kenneth Douglas, B.Sc. (*Durham*).
Irwin, Frederick George Ernest, B.A., B.A.I. (*Dublin*).
Jeffs, Geoffrey Ayling, Stud.I.C.E.
Jennings, Patrick Owen, B.E. (*National*), Stud.I.C.E.
Johnston, John Campbell, B.A., M.A.I. (*Dublin*).
Johnstone, Charles Napier Carruthers, Stud.I.C.E.
Kulczycki, Jerzy Slawomir Andrzej, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Kurpiel, Stanislaw Franciszek.
Lea, Ivor Scrace, B.Sc. (*Cape Town*).
Leach, Duncan Jones, B.Sc. (*Manchester*).
Lickrish, John, Stud.I.C.E.
Lilley, John, B.Sc. (*Durham*).
Longlands, Henry Geoffrey, B.Sc. (*Nottingham*), Stud.I.C.E.
McClure, Robert David, B.Sc. (*Belfast*), Stud.I.C.E.
McNeill, Charles John Neville, B.Sc. (*Belfast*).
Marshall, Clive Turner, B.Sc. (*Leeds*), Stud.I.C.E.
Martin, Robert, B.Sc. (*St. Andrews*).
Mitchell, John Jefferson, B.Sc.(Eng.) (*London*).
Moore, Ronald William, B.Eng. (*Liverpool*).
Myles, Alec Frater, B.Sc.(Eng.) (*London*).
Newman, Kenneth, B.Sc.(Eng.) (*London*), Stud.I.C.E.
O'Brien, Matthew Melville, B.Sc. (*Witwatersrand*).
Ogilvie, Gavin, B.E. (*New Zealand*), Stud.I.C.E.
Ogley, John, Stud.I.C.E.
Palmer, Peter Michael, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Scott, Ronald Arthur, B.Sc.(Eng.) (*London*).
Sehmi, Baldip Singh, Stud.I.C.E.
Simmonds, Harry Keith, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Skillman, John Michael, B.Sc.(Eng.) (*London*).
Slater, Michael, B.Sc.Tech. (*Manchester*), Stud.I.C.E
Sleight, Edward Geoffrey, B.Sc. (Eng.) (*London*).
Studzinski, Stanislaw Henryk, Stud. I.C.E.
Subramani, Duraipillay, B.E. (*Madras*), Stud.I.C.E.
Thurairasasingam, Jeevarathinam Victor, B.Sc.(Eng.) (*London*).
Walshe, Joseph Gerard, B.E. (*National*).
Warmington, John Richard, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Whitting, Alan Charles, B.E. (*New South Wales*), Stud.I.C.E.
Williams, David Leslie, B.Sc. (*Wales*).
Wills, Maxwell Thomas, B.E. (*New Zealand*).
Wilson, Michael Seton Angus, B.A. (*Cantab.*), Stud.I.C.E.
Wood, Malcolm, B.Sc. (*Leeds*), Stud. I.C.E.
Woodvine, Reginald Arthur, B.Eng. (*Liverpool*), Stud.I.C.E.
Yeend, Gerald James, Stud.I.C.E.

and had admitted as

Students

Adams, Robert Charles.
Allan, William.
Allison, Clive.
Antia, Jal Merwanji.
Atkar, Dilbag Singh.
Barnard, David Philip.
Barron, Gerald Percival.
Barton, Philip Richard Jonathan.
Bird, David Cecil.
Boots, Ronald Edward.
Bricheno, Peter Geoffrey.
Brooks, John Alfred.
Brown, Roger Lewis.
Burdet, Jean Laurent.
Burns, Gavin Young.
Campion, Alfred.
Carr, Alan David.
Chatterley, Michael Arthur.
Chaudhry, Rashid Ahmad.
Churchman, Roy Francis.
Clapham, Geoffrey Smith.
Clayden, Kenneth John Charles.
Cockroft, Herbert.
Colloff, John.
Cowle, John
Dann, Anthony Ernest.
Davies, Peter Samuel.
Edwards-Winser, Brian.
Evans, Roy.
Fawkes, Patrick Estcourt.
Fletcher, David.
Fletcher, John.
Gee, Brian Lewis.
Gehring, Hugo Theodor.
Glasgow, Donald.
Gray, Gordon.
Griffin, Ernest John.
Hampton, Barry Charles.
Harle, George Haveron.
Hatch, Barry George.
Heath, Donald Frederick.
Hobbs, Geoffrey John.
Holmes, Ian George.
Holt, John Kendrick.
Jackson, Peter Godfrey Eyre.
Jacobson, Percival William.
Jones, William Leslie.
Jouzy, Raja.
Larsen, Arvid Otto.
Macdonald, Omar Johnston.
Martin, Joseph.
Maxwell, John William Smith.
Meek, Graham Frederick.
Orsborn, Brian John.
Osborne, Gerald.
Over, Brian Leslie William.
Ozanne, John Herbert.
Penny, Bruce Howard.
Pertee, Christopher John.
Pescod, Michael.
Prosser, Michael John.
Reichenbach, Peter Karl.
Relph, Robert Leslie.
Richardson, Anthony Thomas.
Rose, Alan James Elder.
Seddon, Brian.
Serjeant, Patrick Hugh.
Shoreson, Wilfred.
Stark, John.
Stephens, Charles Anthony.
Sutherland, Leslie Davidson.
Tomsett, Henry Naaman.
Wade, James Bernard.
Watson, Douglas Whitelaw.
White, David.
Whitehead, Alan.
Wild, John Patrick.
Williams, Richard Kendrick.
Woodruff, John.
Wright, Bruce Christopher.
Yardley, Laurie.

The following Paper was presented for discussion and, on the motion of the President, the thanks of the Institution were accorded to the Authors.

Paper No. 6017

GEOPHYSICAL METHODS OF EXPLORATION AND THEIR APPLICATION TO CIVIL ENGINEERING PROBLEMS

by

***Jack Robertshaw, B.Sc., A-M.I.C.E.,**

and

Philip Duncan Brown, B.Sc.(Eng.), A.M.I.C.E.

SYNOPSIS

During recent years there has been a definite trend towards the use of geophysical methods to assist site investigation in civil engineering. Although geophysics has been used for many years in mining and oil exploration, it represents a comparatively new technique to the civil engineer, and the main purpose of the Paper is to describe the methods and their application to site investigation.

The Paper deals with the two main methods applicable to site investigation, namely, the electrical resistivity and the seismic refraction methods. The basic principles are given, and the interpretation techniques are discussed. The types of problem to which geophysical surveys can be applied, and the limitations of the methods are discussed. Details of the field equipment and instruments are given, and various field procedures and their applications are described.

The Paper is illustrated by several examples of surveys undertaken by the Authors using both the resistivity and seismic methods.

INTRODUCTION

GEOPHYSICAL methods of subsurface exploration have been developed principally in the fields of oil and mineral prospecting during the past 20 to 30 years, where they are now used very extensively and very profitably. These methods were first applied to civil engineering problems in America about 25 years ago[1] but, until recent years, few geophysical surveys were made in the United Kingdom on civil engineering sites; to many civil engineers the application of these methods of site investigation is still a subject shrouded in mystery. The purpose of the Paper is to draw the attention of civil engineers to geophysical methods of site investigation and to discuss the applications and limitations of these methods.

Geophysics is a science concerned with the physical properties of the earth. The main physical properties exhibited by the earth are magnetism, density, electrical conductivity, and elasticity. Variations in the subsurface geology are accompanied by variations in one or more of these physical properties which can be measured by the geophysicist at the surface of the earth. With the instruments now available these measurements present no difficulty, but it is then the geophysicist's job to try to deduce the changes in the subsurface geology responsible for the changes in the physical properties he has measured and it is here that the real problem lies. Similar geophysical anomalies may sometimes be caused by one of several different geological conditions and careful correlation of the geophysical measurements with the known geology of the area is, therefore, essential. Geophysical surveying is, in fact, a geological tool. The geologist maps what he can see and the geophysicist enables him to explore the hidden geology.

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* At the time of writing the Paper the Authors were both Engineers-in-Charge in the Geophysical Department of Soil Mechanics, Ltd.

[1] The references are given on p. 676.

The first essential in starting a site investigation is to make a geological survey to determine the possible subsurface conditions which may be expected. This should be followed by a geophysical survey, where applicable, in order to obtain a general picture of the subsurface geology, thus providing a basis for the subsequent drilling and testing programme to obtain detailed information where it is most required. Information from the first few boreholes is normally sufficient to provide a control on the interpretation of the geophysical data, from which a more detailed picture of the subsurface conditions between the boreholes can then be obtained.

The advantage of a geophysical survey lies in the speed and economy with which an area can be explored compared with other methods. Indeed, the object is to save money by eliminating unnecessary drill holes and to amplify the information obtained from the holes that are put down. However, geophysical methods of exploration are not applicable in all cases, and must be used with discretion.

Of the several geophysical methods of exploration the electrical resistivity and seismic methods are the ones most usefully applied to civil engineering problems and the Paper is confined to these two methods.

ELECTRICAL RESISTIVITY METHOD

The resistivity of a rock is defined as the resistance offered by a unit cube of the rock to the flow of an electrical current perpendicular to one of its faces. With the exception of certain metallic minerals, the constituent minerals of a rock are insulators of varying effectiveness and the resistivity of a rock depends almost entirely on the amount and salinity of the moisture it contains. The more porous or the more jointed and fissured the rock is, the lower is the resistivity. Thus, in general, igneous rocks have a much higher resistivity than sedimentary rocks, and of the latter, limestones and sandstones are more resistant than shales and clays. It is, of course, upon the extent to which the resistivity of the rocks in a particular area differs, that the success of the survey depends.

To measure the resistivity of the ground an electric current is introduced into the ground through two metal spikes, called current electrodes, which are connected by insulated wires through a milliammeter to a battery or generator. The current flows through the ground in the manner shown in Fig. 1, the lines of flow making a pattern similar to the lines of magnetic force around a bar magnet. Theoretically the current flow extends to an infinite depth, but the intensity diminishes rapidly with depth, and for practical purposes the current can be considered to be confined within a depth equal to approximately one-third of the distance between the current electrodes.

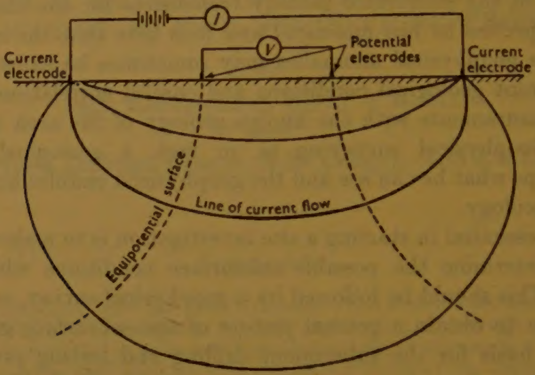


Fig. 1.—Vertical section along line of electrodes showing lines of current flow and equipotential surfaces in homogeneous ground

In uniform ground the lines of flow have a definite shape independent of the resistivity of the medium or the distances between the electrodes, so that, by varying the electrode separation, the current penetration can be varied accordingly.

To measure the resistivity another pair of metal spikes, called potential electrodes, are placed between the current electrodes so that the four electrodes are in a straight line and equally spaced. These potential electrodes are connected by insulated wires to a potentiometer or valve-voltmeter and the voltage drop V between the potential electrodes resulting from a current I applied between the current electrodes is measured. The resistivity of the ground is proportional to V divided by I multiplied by the electrode spacing.[2, 3] One type of resistivity apparatus is shown in Fig. 2 (p. 656). It consists essentially of a high voltage battery supply, a multi-range milliammeter, a multi-range millivoltmeter, and a device for eliminating the effects of polarization at the electrodes, and of small natural currents in the ground. The portability of the equipment, which is essential for speedy operation in the field, should be noted.

In practice the ground rarely consists of a single homogeneous material and the resistivity value so measured is the apparent resistivity of the ground, not the resistivity of some specific rock. It is the variation in the apparent resistivity with either the electrode spacing or position of the electrode system which enables deductions to be made regarding the distribution of the rocks.

Expanding electrode separation technique

One way in which the electrodes can be moved whilst keeping them equally spaced and in a straight line is to expand the electrode system about a fixed central point. As already explained, the depth of penetration of the current into the ground is dependent upon the distance between electrodes, so that by increasing the electrode spacing the depth of current penetration is increased. If the ground is homogeneous the resistivity will be constant for all electrode spacings and equal to the actual resistivity of the material; the graph of resistivity against electrode separation would, therefore, be a constant. Now to be considered is the case of a single homogeneous layer of uniform thickness overlying another homogeneous material of contrasting resistivity extending to an infinite depth. For this example it is assumed that the upper layer has a lower resistivity than the underlying material (Fig. 3). When the electrode separation is small compared with the thickness of the upper layer, practically all the current will flow through the upper layer, and the apparent resistivity measured will approximate closely to the actual resistivity of the upper medium. As the electrode separation is increased the depth of current penetration increases and so does the apparent resistivity measured, as a result of the presence of the underlying material of high resistivity. When the electrode separation is large compared with the thickness of the upper

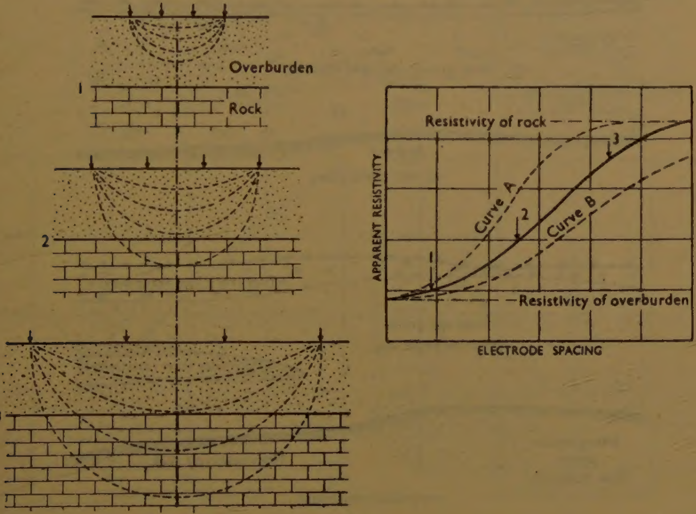
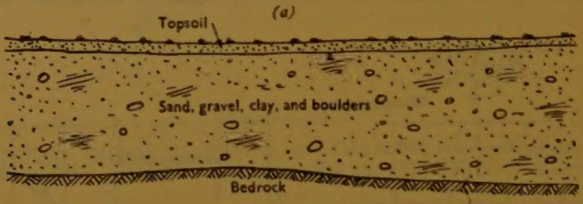


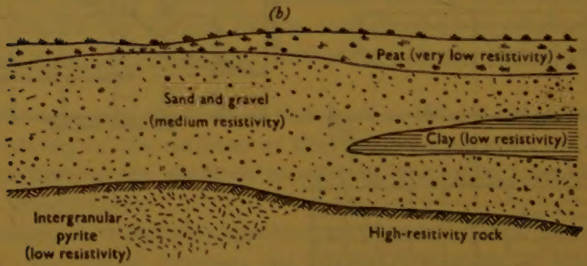
Fig. 3.—Diagrams illustrating the expanding electrode method of resistivity survey

layer, most of the current will pass through the underlying high resistivity material, and the apparent resistivity will then approach the actual resistivity of the underlying material.

If a series of resistivity measurements were made at an increasing electrode spacing, a resistivity curve of the type shown in Fig. 3 would be obtained. The thinner the upper layer, the steeper would be the curve (curve A), and *vice versa* (curve B). In order to determine the depth to the interface the resistivity curve is superimposed on a series of standard theoretical curves which have been computed for various values of depth and resistivity ratio.[4] The depth is then determined from the theoretical curve giving closest agreement with the field curve.



SUITABLE CONDITIONS



UNSUITABLE CONDITIONS

FIG. 4.—CONDITIONS FOR RESISTIVITY SURVEY

An obvious application of this technique is the determination of the depth to bedrock which is overlain by drift, but the accuracy of such a depth determination will depend upon the extent to which the subsurface conditions approximate to the ideal conditions upon which the interpretation is based. A truly homogeneous geological formation never occurs in practice, but a formation which is uniform or shows a regular variation in the mass can be regarded as homogeneous for this purpose. For example, a uniform mixture of sand, gravel, clay, and boulders (Fig. 4a), or a rock consisting of alternating thin bands of sandstone and shale will behave as homogeneous materials, but any irregular variation in the general nature of either the overburden or the rock will usually make a reliable determination of the depth to rock impossible (Fig. 4b). In particular, peat has a very low resistivity, and even a small variation in the thickness of a peat layer may cause variations in the apparent resistivity of the ground sufficient to render the resistivity measurements meaningless. Similarly, concentrations of iron pyrites (or other sulphide deposits) which are always very much better electrical conductors than the rocks in which they are contained effect the apparent resistivity measurements to such an extent as to render the results entirely misleading so far as the determination of the depth to rock is concerned.

Resistivity curves of the type shown in Fig. 5 are frequently obtained in the field and indicate the existence of three different resistivity layers.

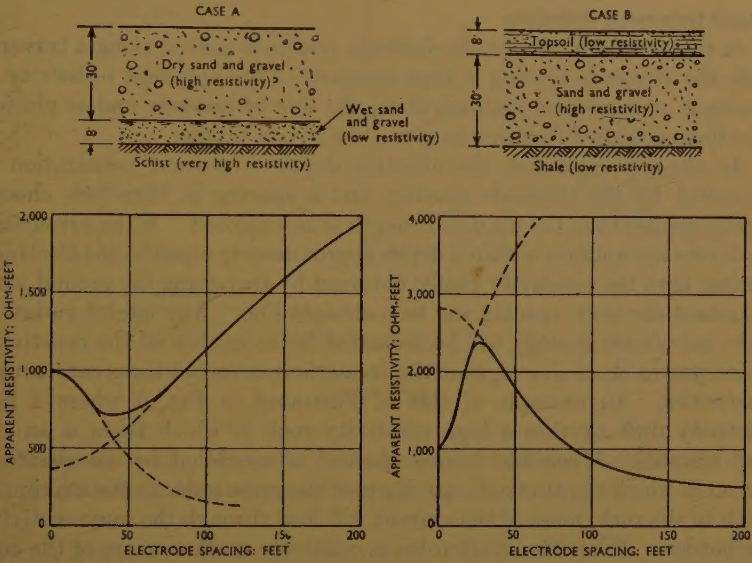


FIG. 5.—RESISTIVITY CURVES FOR TYPICAL THREE-LAYER CASES. THE BROKEN LINES INDICATE THE TWO-LAYER CURVES FROM WHICH THE THREE-LAYER CURVES ARE DERIVED

For example, the existence of a water-table in the overburden would produce this result. In order to determine the total thickness of overburden, only the last part of the curve is used, treating it as part of the curve that would be obtained if the two upper layers were replaced by an equivalent single layer, in the same way as two resistors in parallel might be replaced by an equivalent single resistance.

If the middle layer is thin compared with the thickness of the upper layer it has been found that the trough in the resistivity curve occurs at an electrode separation equal to the depth of that layer below the surface. For example, in the case of a high resistivity bedrock overlain by sand and gravel in which the water-table stands only a few feet above the rock, that part of the overburden below the water-table and immediately above the bedrock would have a low resistivity relative to the dry overburden and the rock. In such circumstances a three-layer curve would be obtained similar to that shown in Fig. 5 (case A), and the trough on the curve would occur at an electrode separation equal to the depth of the water-bearing gravel and, hence, approximately equal to the depth of bedrock. Unfortunately, however, this empirical method of interpretation has been used by some investigators as a standard procedure for determining the depth to rock quite regardless of the actual subsurface conditions.

Lateral traversing technique

In this technique the whole electrode system is moved along a traverse while the electrode spacing is kept constant. The apparent resistivity is measured at successive stations along the line of traverse and is plotted as ordinates against distance to give a resistivity profile.

As already explained, the effective depth of current penetration is controlled by the electrode spacing, and a spacing is, therefore, chosen slightly greater than the maximum depth to be explored. If the subsurface conditions are uniform within a depth approximately equal to the electrode spacing, then the resistivity profile obtained by traversing the ground with a constant electrode spacing will be a straight line. Any lateral variation in the subsurface geology will be indicated by anomalies on the resistivity profile provided, of course, that the formations involved have contrasting resistivities. An example of this is illustrated in Fig. 6 where a low resistivity drift overlies a high resistivity rock in which there is an old river channel. When the buried channel is straddled by an electrode system in which the electrode spacing is of the same order as the maximum depth to the rock, most of the current will flow through the low resistivity overburden. When the overburden is relatively shallow, more of the current will penetrate the high resistivity rock. Hence, a low resistivity anomaly would be obtained when the electrode system traversed the buried channel.

However, lateral variations in either the nature or thickness of any stratum occurring within the effective depth of current penetration may cause similar variations in the apparent resistivity measured at the surface and herein lies the limitation of electrical resistivity methods. Furthermore, small variations in the geology near the surface can effect the apparent resistivity as much as large variations in the geology at depth. Careful correlation of the resistivity measurements with the known geology of the area is, therefore, essential.

The lateral traversing technique is a very rapid and inexpensive method of exploration and, in favourable conditions, a mile of profile can be run in one day. On the basis of the Authors' experience, it is recommended primarily for investigations at shallow depth to link up widely spaced boreholes. For example, it has been used extensively in conjunction with auger holes and test pits for investigating the proposed routes for new roads and pipelines, to delineate those sections where rock is likely to be encountered in the excavations. Another application, in which this technique has been consistently successful, is the location and delineation of the extent and thickness of sand and gravel deposits enclosed in clay.[5]

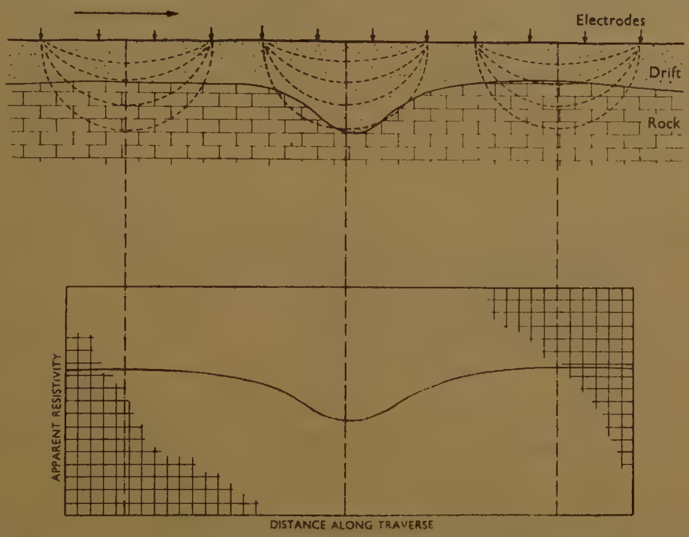


FIG. 6.—DIAGRAMS ILLUSTRATING THE LATERAL TRAVERSING METHOD OF RESISTIVITY SURVEYING

EXAMPLES ILLUSTRATING THE APPLICATION OF THE RESISTIVITY METHOD

Investigation of dam sites

A resistivity survey was made on the proposed site for a dam in the Fiji Islands to determine the order of depth to rock under the river before embarking upon a programme of drilling which was bound to be extremely costly in view of the location of the site and the difficulty of access by canoe up the river. The site was in a steep-sided rock gorge about 200 feet wide. During the ice-age when the world ocean level was about 200 feet below its present level, the river eroded its bed to an unknown depth. Subsequently, the channel was refilled to its present level with alluvial sands and gravel, and with rock debris from the sides of the gorge.

Resistivity measurements were made on a number of sections across the river using the expanding electrode technique. To do this, four ropes were stretched across the river equally spaced about the cross-section to be investigated. the spacing of the ropes corresponding to the electrode separation required. An electrode, connected by an electric cable to the instruments on the bank, was suspended in the water from each rope and arranged in a straight line up and down the river. The electrodes were moved along the ropes in line and the apparent resistivity of the ground was recorded at regular intervals across the river, the whole procedure being repeated with successively increasing electrode separations.

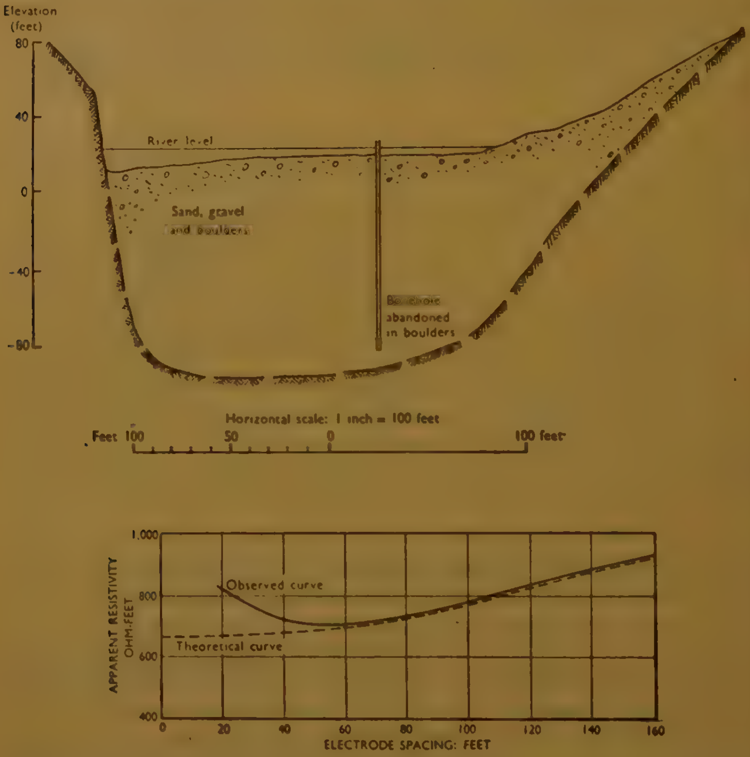


FIG. 7.—INVESTIGATION OF DAM SITE IN FIJI. TYPICAL RESISTIVITY CURVE OBTAINED ON THE SITE AND A SECTION SHOWING THE INTERPRETED ROCK PROFILE

The resistivity curve shown in Fig. 7 is typical of those obtained across the middle of the river, and an interpretation of this curve indicated that the rock surface was about 120 feet deep. Since this was very much deeper than had been thought possible from geological considerations, a small diamond drill was subsequently taken up to the site and a drill hole was put down in midstream, but this was abandoned at a depth of 102 feet in boulders. An inclined hole under the river encountered what was considered to be rock approximately 140 feet below the present sea level.

In the interpretation of a resistivity survey it is assumed that the rock is of an infinite extent. This assumption was justified on this site because the rock was only expected to be a maximum of 50 feet deep and therefore the limitations due to the width of the gorge could be ignored. However, since the rock was proved to be almost as deep as the width of the gorge this assumption was not applicable. The presence of the rock in the sides of the gorge caused an under-estimate of the true rock depth. In fact the resistivity survey indicated an average depth and not the maximum.

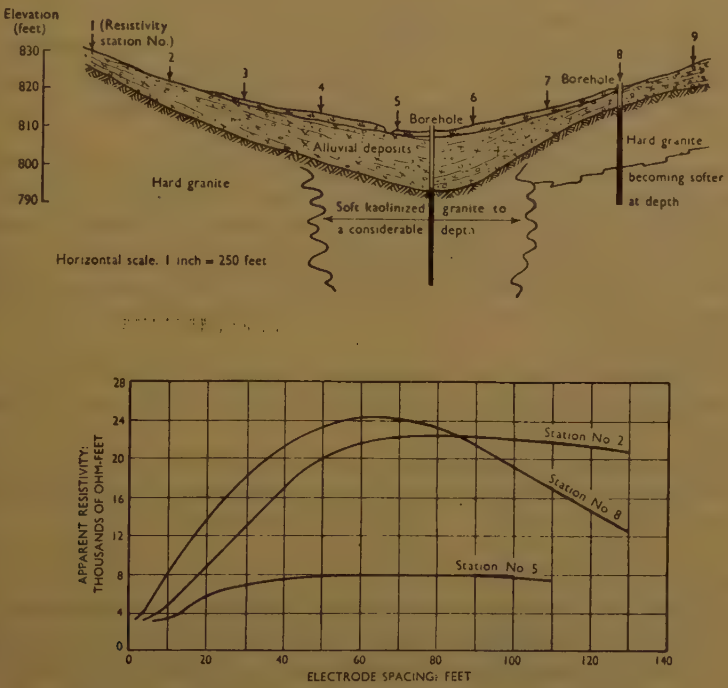


FIG. 8.—PROPOSED CUT-OFF WALL SITE IN CORNWALL. INTERPRETED GEOLOGICAL SECTION ALONG THE CENTRE-LINE OF THE CUT-OFF WALL AND TYPICAL RESISTIVITY CURVES OBTAINED ON THE SITE

Another example of a resistivity survey, made on a site for a cut-off wall in Cornwall, serves to illustrate what can be done by the close correlation of geophysical and geological data.

The rock was known to be granite and was overlain by a mixture of clay, sand, and gravel. The valleys in this area are often found to be an expression of a zone of kaolinized granite which is softer and more easily eroded than the hard fresh granite, and it was suspected that this valley would prove to be such a zone.

Resistivity measurements using the expanding electrode separation technique were made at nine stations across the valley and three distinct types of curve were obtained. One of each type is shown in Fig. 8. The curve at station No. 8, typical of those obtained on the right flank, is a three-layer curve indicating the presence of a low resistivity material, that is, the overburden, underlain by a very high resistivity material, underlain by a material of intermediate resistivity. Curve No. 2, typical of those obtained on the left flank, approximates to a two-layer curve, though the resistivity of the lower layer decreases slightly at depth. Curve No. 5 obtained in the centre of the valley is also a two-layer curve indicating a low resistivity layer, that is, overburden, overlying a material of higher resistivity, but in this case the very high resistivity layer found on the other two curves is absent.

Bearing in mind the known geology of the area, it was concluded that the three-layer curves obtained on the right flank represented overburden overlying fairly hard granite underlain by soft kaolinized granite. On the left flank, the slight falling-off in resistivity at depth suggested that the granite was slightly kaolinized at depth, and in the valley bottom between stations Nos 4 and 7 it was concluded that the soft kaolin extended to the surface of the rock.

The thickness of the overburden was determined by considering only the first part of the resistivity curves and interpreting them as two-layer curves.

Two boreholes were subsequently drilled and confirmed this interpretation and, thus, a complete picture of the subsurface geology was constructed as shown in Fig. 8.

Survey of a gravel deposit

A typical resistivity survey to delineate the extent and thickness of a gravel deposit is illustrated in Fig. 9. A geological reconnaissance had shown that there was a bed of alluvial gravel overlying the Lias Clay, and the problem was to determine the amount of gravel that would be available for the construction of a road diversion embankment.

A series of resistivity traverses was run across the site with a constant electrode separation of 20 feet, and a map showing lines of equal resistivity was constructed from the measurements thus obtained, as shown in Fig. 9.

The clay was known to extend to an appreciable depth, and the only formations occurring within 20 feet of the ground surface were the gravel and clay. Any variation in the apparent resistivity of the ground at an electrode separation of 20 feet could, therefore, be attributed entirely to the variation in thickness of the gravel. Clay has a higher moisture content and contains more dissolved salts than gravel and, in consequence, gravel has a much higher resistivity than clay, even if the gravel is water-bearing.

Hence, the high resistivity zone on the resistivity-contour map indicated the greatest thickness of gravel.

A theoretical calibration curve was constructed correlating apparent resistivity with gravel thickness, and three borings were made to check this curve, and to determine the quality of the gravel. Using the calibration curve in conjunction with the equi-resistivity-contour map, another map was drawn showing lines of equal gravel thickness from which an

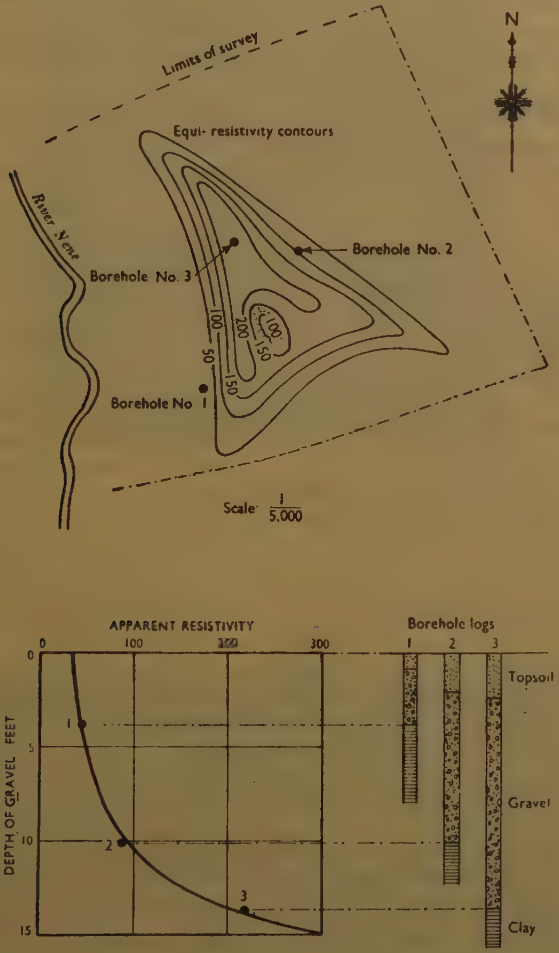


FIG. 9.—RESISTIVITY SURVEY FOR GRAVEL IN NORTHAMPTONSHIRE. SITE PLAN SHOWING EQUI-RESISTIVITY CONTOURS AT AN ELECTRODE SPACING OF 20 FEET AND CALIBRATION CURVE CORRELATING RESISTIVITY WITH DEPTH OF GRAVEL

estimate was made of the quantity of gravel available. This resistivity survey was completed in one day.

Survey for a pipeline

A resistivity survey was made in Scotland to determine the amount of rock excavation that would be necessary along a proposed pipeline trench 7 feet deep and 40 miles long. The pipeline route traversed undulating agricultural land where glacial drift overlay rocks consisting mostly of sandstones.

A geological reconnaissance was made to locate areas where a substantial thickness of drift overlay the route, to map outcrops near to the route, and to identify rock types. Apparent resistivity measurements were made using a constant electrode spacing of 20 feet along the proposed route. A continuous resistivity profile was obtained, a small part of which is shown in Fig. 10. The anomalies on this profile were carefully correlated with the geological data, and it was found satisfactory to interpret the resistivity data by considering the ground as a two-layer structure consisting of low resistivity overburden over a high resistivity rock. Hence, high resistivity values were recorded for those sections where the rock was close to the surface.

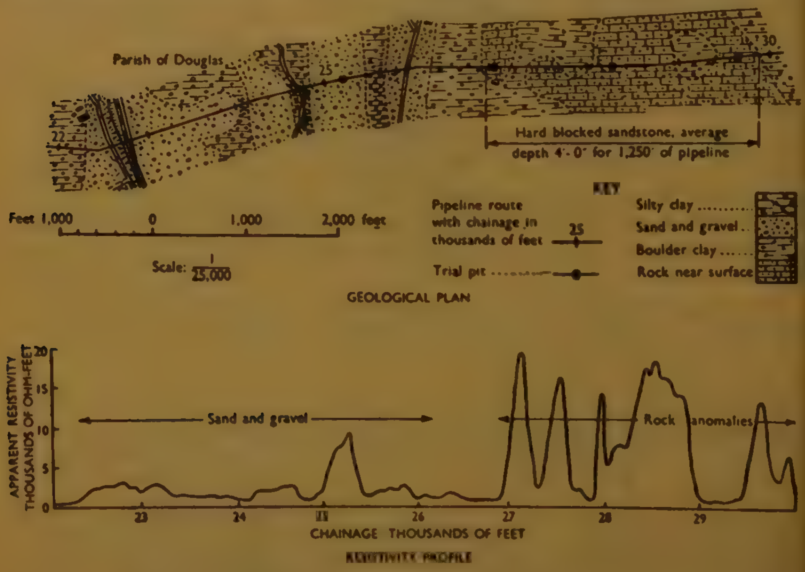


FIG. 10.—RESISTIVITY SURVEY OF PIPELINE IN SCOTLAND

The interpretation was checked by pits and auger holes where the resistivity data indicated that the rock was close to the surface. The route was surveyed at the rate of one mile per day.

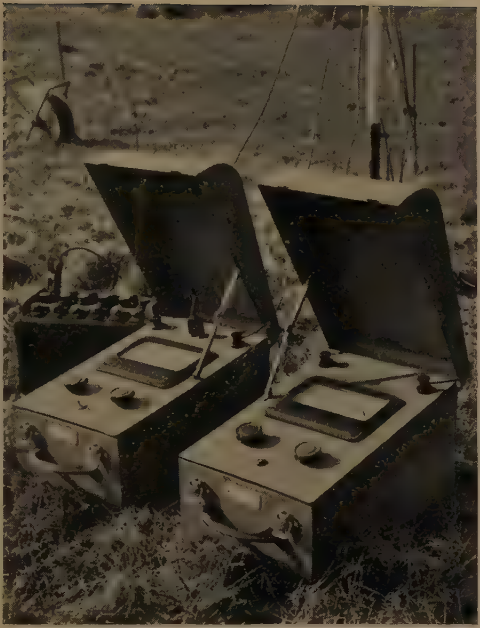


FIG. 2.—RESISTIVITY EQUIPMENT WITH THE POWER SUPPLY AND CURRENT-MEASURING UNIT ON THE LEFT, AND THE MILLIVOLTMETER ON THE RIGHT

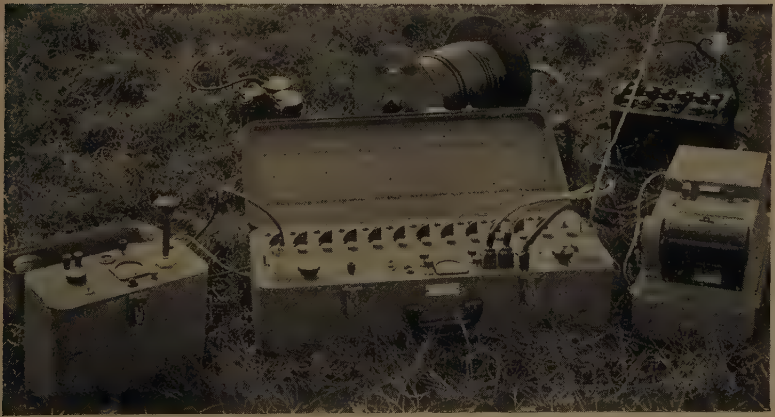


FIG. 16.—SEISMIC REFRACTION EQUIPMENT, COMPRISING SHOT-FIRING UNIT, 12-CHANNEL AMPLIFIER CASE, AND RECORDING CAMERA. THREE SEISMOMETERS CAN BE SEEN IN THE BACKGROUND

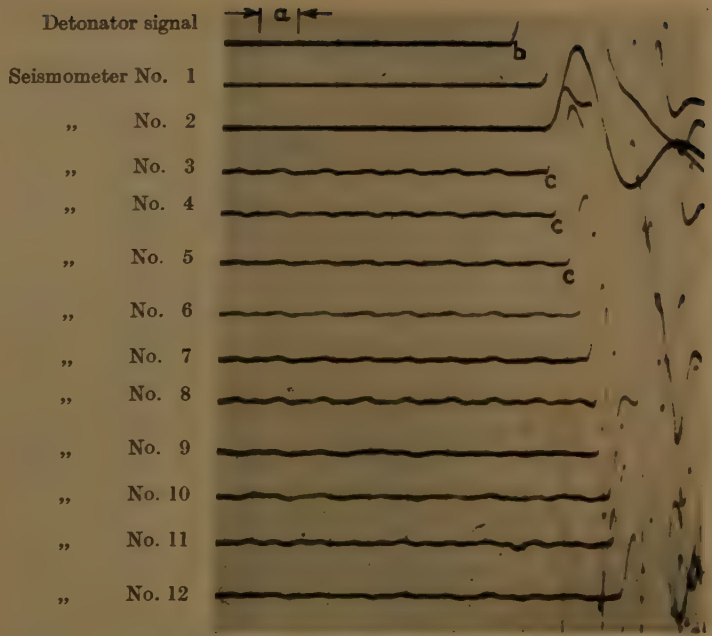


FIG. 17.—SEISMIC REFRACTION RECORD SHOWING THE SIGNALS FROM THE DETONATOR CIRCUIT AND TWELVE SEISMOMETERS

(a) denotes interval of 0·01 second
(b) „ instant of shot
(c) „ instant vibration reaches seismometers

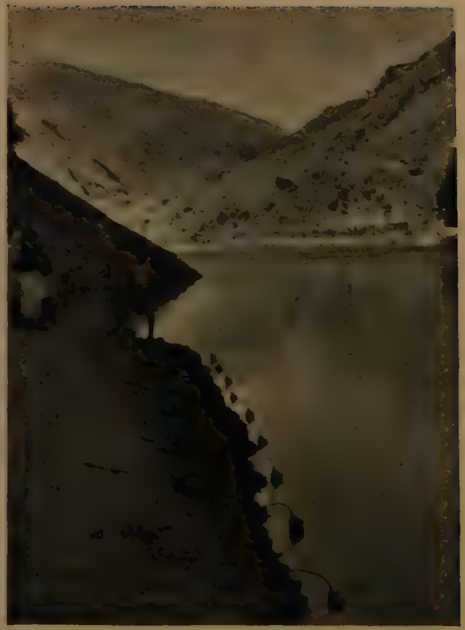


FIG. 20.—SEISMIC SURVEY OF PROPOSED DAM SITE IN PAKISTAN, SHOWING LINE OF SEISMOMETERS

SEISMIC METHODS

The seismic methods of subsurface exploration are used primarily for determining the depth to formation boundaries, and in this respect they have a much greater resolving power than any other geophysical method.

Seismic methods are the most extensively used of all the geophysical methods for oil exploration. Their application to exploration at the relatively shallow depths encountered in civil engineering is comparatively new and very successful.

There are two quite distinct methods of seismic exploration, the refraction method which uses the refraction of elastic waves at physical discontinuities in the ground, and the reflexion method in which the reflexion of elastic waves at subsurface discontinuities is considered. The reflexion method has its greatest application in the exploration of deep formation boundaries. It has been used successfully in exploring to depths of 20,000 feet, but it is not suitable for the relatively shallow exploration of civil engineering sites. However, the refraction method can be readily applied to these investigations and is particularly suitable for determining the depth to a consolidated layer or bedrock.

THE REFRACTION METHOD

A sudden elastic disturbance is set up in the ground by exploding a small charge of gelignite and the resulting seismic waves, transmitted through the ground, are picked up by a number of vibration detectors (seismometers) located on the ground surface. The seismometers transform the ground vibrations into electrical impulses which are transmitted to a recording apparatus where they are amplified and recorded on photographic paper moving at high speed. The instant of explosion and time markings are also recorded. In this manner the interval of time between the instant of explosion and the arrival of the first vibration impulse at each seismometer is determined.

In order to see how this travel time data is used to determine the depth to a formation boundary, the simple case illustrated in Fig. 11 may be cited. It represents the advance of a wave-front in a two-layer structure consisting of bedrock overlain by drift. For the purpose of this illustration it has been assumed that seismic waves will travel through the overburden and bedrock at velocities of 5,000 feet per second and 10,000 feet per second respectively. If an explosion is detonated at the shot point S, elastic waves having a spherical wave-front will travel outwards from the point of explosion at a velocity of 5,000 feet per second. According to Huygen's principle,[2, 3] every point on the wave-front will be a new source of spherical waves, and the wave-front at any later time will be the surface tangent to these new spherical waves.

When the wave-front reaches the surface of the rock it continues to

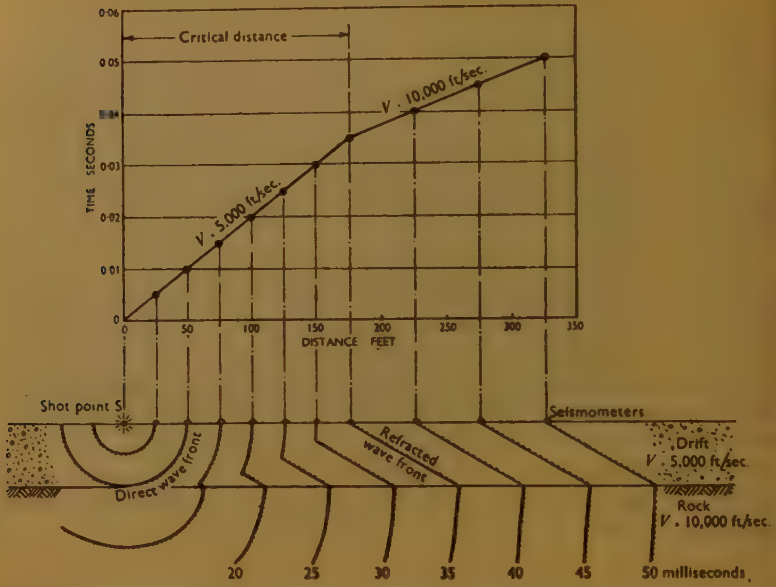


FIG. 11.—GROUND SECTION SHOWING ADVANCE OF A SEISMIC WAVE FRONT THROUGH A TWO-LAYER STRUCTURE AND THE RESULTANT TIME/DISTANCE GRAPH

advance in all directions through the rock at a velocity of 10,000 feet per second. As the wave-front advances in the rock along the rock surface it starts a new series of waves (in accordance with Huygen's principle) which travel from the rock surface back to the ground surface through the overburden at a velocity of 5,000 feet per second. The envelope of these new waves travelling towards the ground surface is the refracted wave-front. Fig. 11 shows the advance of the wave-front for times up to 50 milliseconds after the instant of explosion; from this it will be evident that at the seismometers on the ground surface close to the shot point S, the first waves to arrive will be those which have travelled directly through the overburden with a velocity of 5,000 feet per second. Farther from the shot point there is a critical point at which the waves that have been refracted from the rock surface arrive at exactly the same instant as the direct waves travelling through the overburden, and at distances greater than this critical distance from the shot point the first arrival will always be the refracted wave-front.

If the interval of time between the instant of shot and arrival of the wave-front at each seismometer is recorded and plotted graphically against the distance of the seismometer from the shot point, a time/distance graph consisting of two straight lines intersecting at the critical distance would be obtained, as shown in Fig. 11. It will be evident from the foregoing that the slope of the first curve of this time/distance graph will give the wave velocity through the overburden, and the slope of the second will give the wave velocity through the bedrock.

In the interpretation of seismic data it is convenient to represent the propagation of the seismic waves by means of wave rays. By definition, a wave ray is a wave path which is normal to the progressing wave-front at every instant and is, therefore, a path of minimum time, that is, it is the quickest path between the shot point and a point on the wave-front but it is not necessarily the shortest path.

Fig. 12 shows the path of the wave rays between the shot point and eight seismometers equally spaced along the ground surface for the simple two-layer structure considered previously. In practice, three quantities are required in order to construct a wave-ray diagram; these are, the critical distance x, the critical angle of incidence i, and the depth to the rock surface D. According to Snell's law,[2, 3] the critical angle of incidence may be obtained from the expression:

$$\sin i = \frac{V_1}{V_2}$$

where V_1 denotes velocity of transmission of elastic waves through upper layer.

and V_2 ,, velocity of transmission of elastic waves through lower layer.

It has already been shown that the velocities V_1 and V_2, and the critical distance x can be obtained from the time/distance curve and, hence, the only quantity remaining to be determined is the depth to the rock surface. Bearing in mind that the direct and refracted wave-fronts arrive at the critical point simultaneously, by equating the travel times along the wave paths SC and SABC shown in Fig. 12, an expression for the depth to the rock surface D may be obtained in terms only of the quantities V_1, V_2, and x determined from the time/distance curve thus:

$$D = \frac{x}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

A simple two-layer structure has been used to demonstrate how the seismic data may be used to determine the depth to a formation boundary but, by an extension of this analysis, the depth to one or more deeper boundaries may be determined. The only requirement is that the boundary to be explored must separate two formations in which seismic waves are transmitted at a high velocity through the underlying formation. This requirement is always satisfied in the case of drift overlying bedrock and the seismic refraction method is, therefore, ideally suited to the problem of determining the depth to bedrock on civil engineering sites.

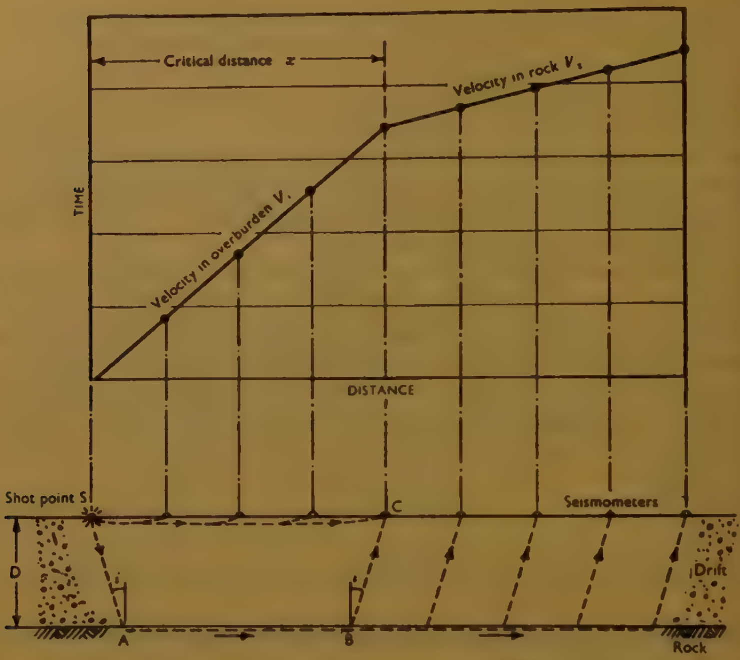


FIG. 12.—TIME/DISTANCE GRAPH FOR TWO-LAYER STRUCTURE AND SECTION SHOWING REFRACTED WAVE RAYS

Sloping bedrock surface

The slope of the second portion of the time/distance curve will give the velocity of wave transmission through the bedrock directly only if the overburden is of uniform thickness. If the rock surface is dipping relative to the ground surface, the slope of the time/distance curve will be a function of both the velocity through the rock and the angle of dip of the rock surface relative to the ground surface. This point is illustrated in Fig. 13. However, in practice, a shot is fired from each end of the seismometer spread in turn so that two time/distance curves for the same seismometer spread can be constructed from the seismic records thus obtained, as shown in Fig. 13. This is equivalent to obtaining two equations from which the two unknown quantities, the angle of dip, and the velocity in the rock can be determined. Having determined these quantities, the depth to rock under each shot point can be determined as before.

Irregular rock surface

Profiling an irregular rock surface by the seismic method presents no difficulty providing three quantities, namely, the wave velocities through the overburden, through the bedrock, and the depth to rock at one point on the site can first be determined.

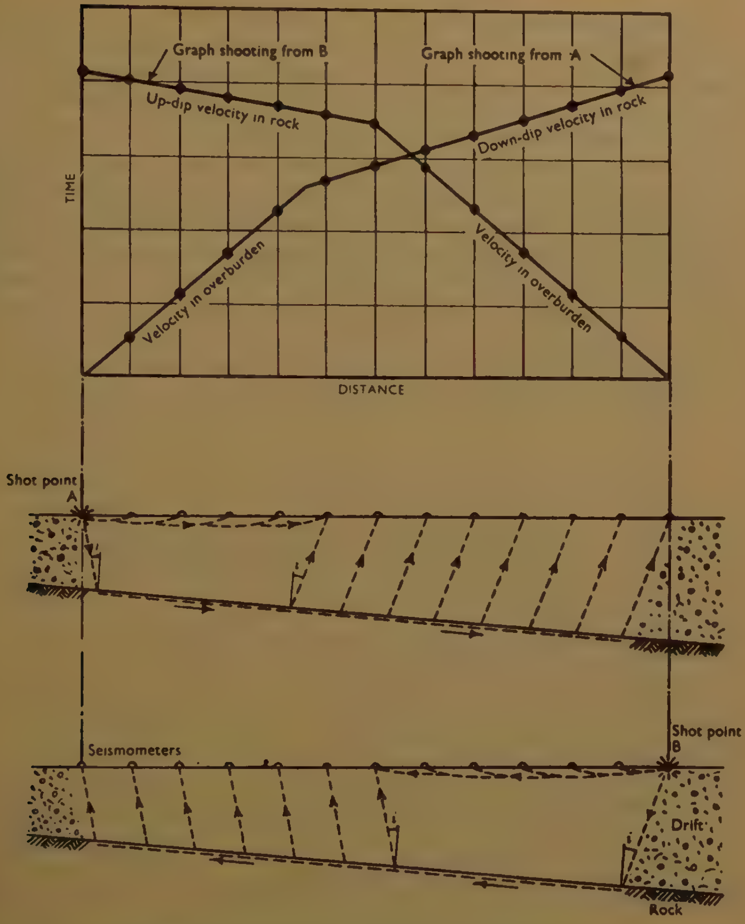


FIG. 13.—TIME/DISTANCE GRAPHS FOR SLOPING ROCK SURFACE AND SECTIONS SHOWING REFRACTED WAVE RAYS

A time/distance curve for a typical irregular rock profile is shown in Fig. 14. As in the previous case, the wave velocity through the overburden can be obtained from the first part of the time/distance curve but the slope of the second part of the curve varies as the slope of the rock surface varies and it will be evident from Figs 15 that the wave velocity through the rock cannot be obtained from this curve. However, the velocity in the rock can usually be determined from the time/distance curve obtained elsewhere on the site where the rock profile is straight. Alternatively, this velocity can be determined directly by making seismic measurements between two rock outcrops or between two boreholes where the depth to rock is known.

In order to determine the profile of an irregular rock surface from the seismic data, the depth to the rock surface under one shot point on the traverse must first be known, and it is usual to locate the first shot point at a rock outcrop or at a borehole, or at some point which has been tied by means of another seismic traverse to a point where the depth to rock has been previously determined. Having established the velocities of wave transmission through the overburden and bedrock and the depth to the rock surface at the first shot point on the traverse, the rock profile can be constructed graphically from the time/distance curve by plotting the wave rays from the shot point to each seismometer station, as illustrated in Fig. 14. By shooting a series of overlapping seismometer spreads, a continuous rock profile is obtained for any required distance, from a few hundred feet to several miles, at the rate of between 600 feet and 1,000 feet per day depending upon the location and conditions on the site. There is no doubt that to obtain similar information entirely from closely spaced borings would be a very long and costly business.

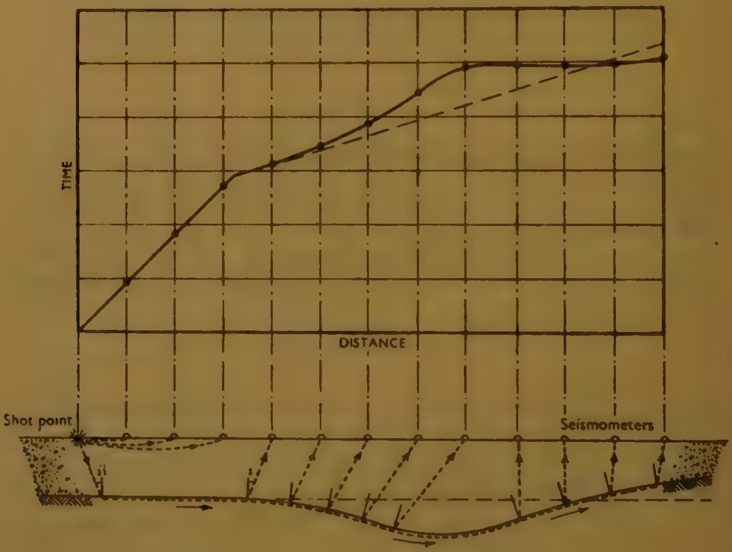


Fig. 14.—Time/distance curve for irregular rock surface and section showing refracted wave rays

Arc shooting

So far, the only seismometer lay-out that has been considered is that in which the seismometers are placed in a straight line. This technique is referred to as profile shooting and is the one most frequently employed for the investigation of engineering sites. However, another technique referred to as arc shooting because the seismometers are arranged on an arc round the shot point, can be usefully applied to mapping the course of buried channels in the rock surface.

In arc shooting the shot point is placed over the centre of the deep channel at a point where the channel has been located previously by seismic methods or by borings. The radius of the seismometer arc must be sufficiently large for the first arrival at every seismometer to be a wave that has been refracted from the rock surface—usually 4 to 5 times the maximum anticipated depth to the rock surface. The travel time between the instant of shot and arrival of the first impulse at each seismometer is recorded, and it will be evident from Fig. 15a that the greatest time travel will be recorded at the seismometer which is directly over the channel. This seismometer station is made the shot point for the next seismometer arc, and by proceeding in this manner the course of the deep channel is traced in plan (Fig. 15b).

Seismic equipment

Seismic refraction equipment containing from three to twenty-four recording channels is available, but the Authors have found twelve-channel equipment to be the most economical in operation on civil engineering sites. Such a set of equipment consists essentially of twelve seismometers, an amplifier unit containing twelve individual amplifiers, one for each seismometer, a thirteen-channel recording oscillograph, and an exploder. The power required to operate the amplifiers and recording unit is provided by a single 12-volt accumulator. A photograph of the equipment used by the Authors is shown in Fig. 16 (p. 656). It is very compact and portable, weighing less than 250 lb. including all the ancillary gear, and can be broken down into convenient one-man loads.

The seismometers usually consist of an electromagnetic device in which a coil acts as the inertia element and a magnet is fixed to the case of the seismometer which is in contact with the ground. Thus, any movement of the ground causes a movement of the magnet relative to the coil and generates a small voltage in the coil. Modern seismometers are quite small, with a weight ranging from 1 to 3 lb.

Each seismometer is connected by a cable to an amplifier which greatly magnifies the small electrical impulse generated in the coil. The output of each amplifier is connected to a moving-coil galvanometer in the recording oscillograph. The coil of each galvanometer carries a small mirror from which a beam of light is reflected and focused as a fine spot on a strip of photographic recording paper, driven through the camera at a speed of approximately 2 feet per second. Any electrical impulse reaching the galvanometer coil causes a deflexion of the spot of light on the photographic paper. The thirteenth galvanometer in the recording oscillograph is connected to the detonator circuit so that the detonation of the explosive charge is similarly recorded on the photographic paper.

A timing device in the recorder, usually actuated by a tuning-fork oscillator or vibrating reed, puts a thin line across the record at intervals of 0·01 second ; hence, the interval of time between the instant of explosion

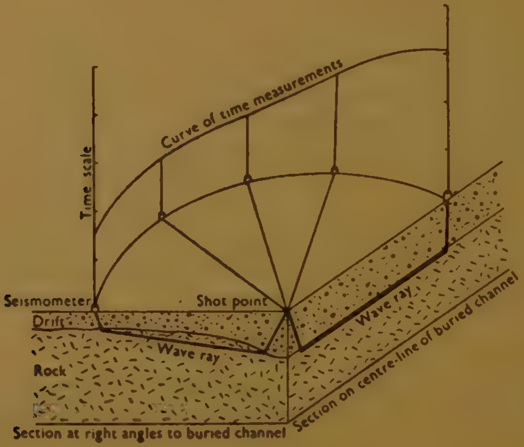

Curve of time measurements
Time scale
Seismometer
Shot point
Drift
Wave ray
Rock
Wave ray
Section at right angles to buried channel
Section on centre-line of buried channel

FIG. 15a.—WAVE-RAY PATHS WHEN ARC-SHOOTING OVER A BURIED CHANNEL AND RESULTANT TIME CURVE

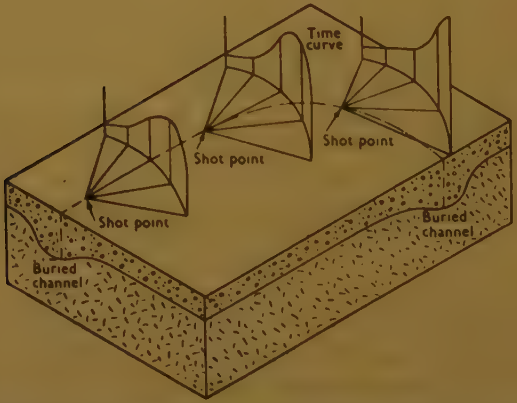


FIG. 15b.—TRACING OF BURIED CHANNEL BY A SERIES OF ARC SHOTS. CENTRE OF CHANNEL IS INDICATED BY HIGHEST POINT ON EACH TIME CURVE

and the arrival of the resulting seismic waves at each seismometer can be obtained from the photographic record. A typical record is shown i Fig. 17 (p. 657). The thin vertical lines on the record represent the tim markings at intervals of 0·01 second, and the thirteen horizontal lines, th signals from twelve seismometers and the detonator circuit. The maximum overall amplification of modern seismic equipment, that is, the ratio of the amplitude of the response on the record to the amplitude of the ground movement at the seismometers, is about 4×10^6. The amount of amplification that can be used on a particular site is governed by the amplitude of the extraneous vibrations (" noise ") in the ground, in particular, those resulting from wind and road traffic, which are picked up by the seismometers. In practice, the amplification of each channel in the seismic equipment is reduced by means of a volume control until the " background noise " on the seismic record is barely noticeable. When the noise level is very high it is sometimes overcome by increasing the size of the explosive charge, and reducing the amplification still further.

Field procedure

A seismic survey crew usually consists of seven men ; observer, shooter, surveyor, and four labourers. The surveyor is responsible for setting out the traverse lines, pegging, and levelling the seismometer stations and shot holes. The observer is responsible for laying out the seismometers and cables and setting up and operating the recording equipment. The shooter is responsible for making the shot holes, laying out the firing line, and placing and firing the explosive charges.

The spacing of the seismometer stations and shot holes depends upon the depth to be explored and the detail required. For example, on a site where it is required to profile the rock surface in detail and the depth is not likely to exceed 50 feet, a seismometer spacing of 10 feet to 20 feet, and a shot hole spacing of 100 feet to 150 feet would be required ; but where the depth of investigation is between 100 feet and 200 feet and only a preliminary reconnaissance is required, a seismometer spacing of 30 feet to 50 feet, and a shot hole spacing of 200 feet to 300 feet would be adequate.

The distance over which seismic measurements are made from a given shot hole position is referred to as the " seismometer spread." The length of the spread depends upon the depth of the investigation and the velocities of wave transmission through the subsurface formations concerned ; a spread of 5 to 8 times the depth is usually required on civil engineering sites. Frequently, this spread must be shot in two or more sections. For example, if a spread of about 500 feet in length is required with a seismometer spacing of 20 feet, one record would be taken with the twelve seismometers spaced from 20 feet to 240 feet from the shot hole, and a second record would be taken with the seismometers spaced from 240 feet to 480 feet from the same shot hole. The two sections of the spread must, of course, be tied by a seismometer station that is common to both sections.

Whenever possible, the seismometers should be placed in small holes in the ground to protect them from the wind. Preferably the holes should be made so that the seismometers are a tight fit, thus obtaining better contact between the ground and the seismometer. The shot holes are usually bored with a hand auger and crowbar, to a depth which depends upon the size of the charge to be used. With the sensitive seismic equipment now available, more than 1 lb. of gelignite is rarely necessary and ¼ lb. is usually adequate for the investigation of engineering sites. To prevent breaking of the ground surface by the explosion, a ¼-lb. charge should be placed at a depth of not less than 4 feet and a 1 lb. charge at a depth of not less than 6 feet.

The Authors have found it convenient to set up the recording equipment in a small light-proof tent which not only affords shelter but serves as a dark room in which the photographic records can be developed on the site. The cables connecting the seismometers to the recording equipment should be preferably not less than 500 feet in length in order that the seismometers can be traversed about 1,000 feet (that is, 500 feet on each side of the recording station) without moving the recording equipment. In this way a full day's work can be done from one instrument set-up, saving time that would otherwise be lost dismantling, moving, and setting up the equipment. When all preparations have been made for the taking of a record, field telephone or radio contact is maintained between the observer and the shooter until the shot has been fired.

POSSIBLE SOURCES OF ERROR IN THE INTERPRETATION OF SEISMIC MEASUREMENTS

Measurement of travel time

The travel times can be determined normally from the seismic record to an accuracy of one millisecond without difficulty and, under favourable circumstances, an accuracy of half a millisecond can be obtained. An error of one millisecond represents an error of about 1 foot to 3 feet in the determination of the depth to a formation boundary; the actual error depends upon the velocity of transmission through the formations, and is usually of significance only when the depths to be determined are very shallow.

Variation of velocity of transmission through a formation

Minor variations in the general nature of a formation, for example, the distribution of boulders or the presence of thin beds of a different material, do not materially influence the transmission velocity of the formation as a whole because the physical dimensions of these irregularities are small compared with the wave lengths of the vibrations. A check on the velocities in the formations concerned is obtained from the time/distance curves on each seismometer spread, and it has been found that no significant error is introduced by assuming that the velocities through the formations are uniform throughout the length of the spread. One exception occurs in the case of peat in which local variations in the velocity of transmission have been found on occasions to be appreciable. For this reason, it is recommended that seismometers should be supported on steel bars driven through the peat into the underlying material whenever practicable. In this manner the layer of peat is, in effect, replaced by a layer of steel through which the seismic waves travel at a known constant velocity.

Unusual velocity distribution with depth

It frequently happens that the overburden overlying the bedrock is made up of two layers having different transmission velocities. Usually the deeper layer transmits the seismic waves at a higher velocity than the surface layer; the existence of a water-table in the overburden would cause such a condition. Refraction of the seismic waves will occur along the interface between the two layers but, unless the deeper overburden layer is of sufficient thickness, these refracted waves will be overtaken by the waves refracted from the surface of the underlying high velocity bedrock and will never be a first arrival at the ground surface. Hence, although the subsurface may consist of three layers having different velocities of transmission the seismic time/distance curve indicates the existence of two layers only, namely, the low velocity surface layer and the high velocity bedrock, as illustrated in Fig. 18. Using the velocities indicated by the

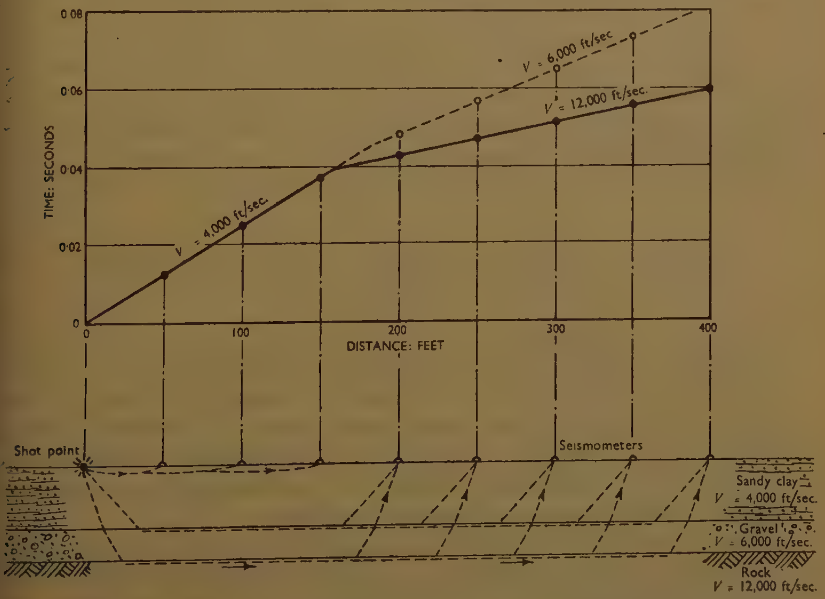


FIG. 18.—SECTION SHOWING REFRACTED WAVE RAYS FOR A THREE-LAYER STRUCTURE. In this particular case refraction from the second layer (gravel) is not indicated by the time/distance graph since it occurs later than refraction from the rock. This later arrival is represented by the broken line on the graph

time/distance curve, the interpreted depth to the rock surface would lie somewhere between the depth to the first interface and the actual depth to rock. This case of a missing layer is not a common occurrence and will arise only under certain conditions, depending upon the relative values of the three velocities and the relative thickness of the two layers comprising the overburden. It is always advisable to check the velocity of transmission through the overburden as indicated by the time/distance graphs against a direct measurement of the velocity, by measuring the travel time of the seismic waves between two points where the subsurface conditions are known precisely. An alternative check on the overburden transmission velocity can be obtained by means of a velocity survey in the borehole, that is, by measuring the travel time of the seismic waves generated by a small explosion at the ground surface to a number of seismometers placed at known depths in a borehole.

If the velocities through the overburden obtained by direct measurement are greater than those indicated by the time/distance graphs, the existence of a high velocity layer in the overburden is indicated and an allowance is made for this in the interpretation of the seismic data. Conversely, if the velocities through the overburden obtained by direct measurement are lower than those indicated by the time/distance graphs, existence of a lower velocity layer underlying a high velocity layer is indicated. In this case, the seismic waves would be refracted downwards and not upwards at the interface between the high velocity layer and underlying low velocity layer and, hence, no indication of the presence of the low velocity layer would be obtained on the time/distance graphs. In these circumstances, experience has shown that no serious error is introduced by using an average overburden velocity, obtained by direct measurement as discussed above, in the interpretation of the seismic data.

EXAMPLES ILLUSTRATING THE APPLICATION OF THE SEISMIC REFRACTION METHOD

Investigation of dam sites in Eire

The survey was made on four possible dam sites on the Avonmore Hydro-Electric project in Eire to determine the depth to rock. A few trial pits and borings had been made on the sites and these were used to calibrate the survey results. The sites were on the Avonmore and Vatry rivers, where the overburden consisted of morainic drift, overlying a bedrock of Lower Palaeozoic slates and quartzites.

On each site the investigation was made with a seismic traverse along the centre-line of the proposed dam. Each traverse consisted of several seismometer spreads ranging in length from 275 to 500 feet, and shots were fired at each end of the spreads. A few additional shots were fired with seismometers close to the shot points in order to determine accurately the velocity in the overburden.

The time/distance graphs for one of the sites are given in Fig. 19, beneath a cross-section of the site showing the interpreted rock profile. The depth to the rock under each shot point was calculated from the velocities and critical distances obtained from the time/distance graphs. The rock profile between the shot points was obtained by graphical construction of the wave ray paths. On this site the eastern side of the river presented a three-layer case ; this is well illustrated by the two graphs on the extreme right of Fig. 19, which have three distinct slopes. The first slope indicates a velocity of 3,000 feet per second in the drift above the water-table, the second a velocity of 8,500 feet per second in the well compacted morainic drift beneath the water-table, and the third the bedrock velocity of 15,300 feet per second.

Only two borings were made on this site but it is evident from the section that several boreholes would have been necessary to obtain the rock profile without the aid of the seismic survey. As a result of the survey on all four dam sites, the borings were kept to a minimum and used mostly for sampling the overburden and for permeability tests.

Investigation of dam site across a gorge

This example is given to illustrate the use of the seismic survey over water where exploration by normal boring methods is usually slow and expensive. This survey was made on the site of a proposed hydro-electric project in Pakistan where the river Kabul passes through a steep-sided gorge about 300 feet wide. Bedrock consisting of metamorphosed granites and schists is exposed in the sides of the gorge, but is covered in the river by a thick deposit of sand, gravel, and boulders. Borings previously drilled in the river indicated a considerable variation in depth to rock. The main purpose of the seismic survey was to determine the rock profile at forty sections across the river at intervals of 75 feet along the gorge, in order to select the most favourable sites for the main dam and cofferdams.

It was intended to make a survey by placing seismometers on the river-bed along the line of section across the river, and firing charges at each end of the section on the river banks. However, it was found that the disturbance of the seismometers by the fast flowing water was too great and the procedure was, therefore, reversed. A seismometer was placed at each end of the section on the river banks, and charges of approximately 3 lb. of gelignite were fired at intervals of 40 feet along the section on the river-bed. The velocity in the overburden was determined by measuring the " up-hole " time in boreholes, and by firing a charge on the bank of the river with seismometers placed close to the shot as illustrated in Fig. 20. Similar direct measurements of the rock velocity were made on the outcrops along the sides of the gorge. These velocity measurements were used to interpret the time/distance graphs by drawing the wave ray paths. The time/distance graphs for one of the sections are given in Fig. 21 together with the corresponding cross-section showing the interpreted rock profile.

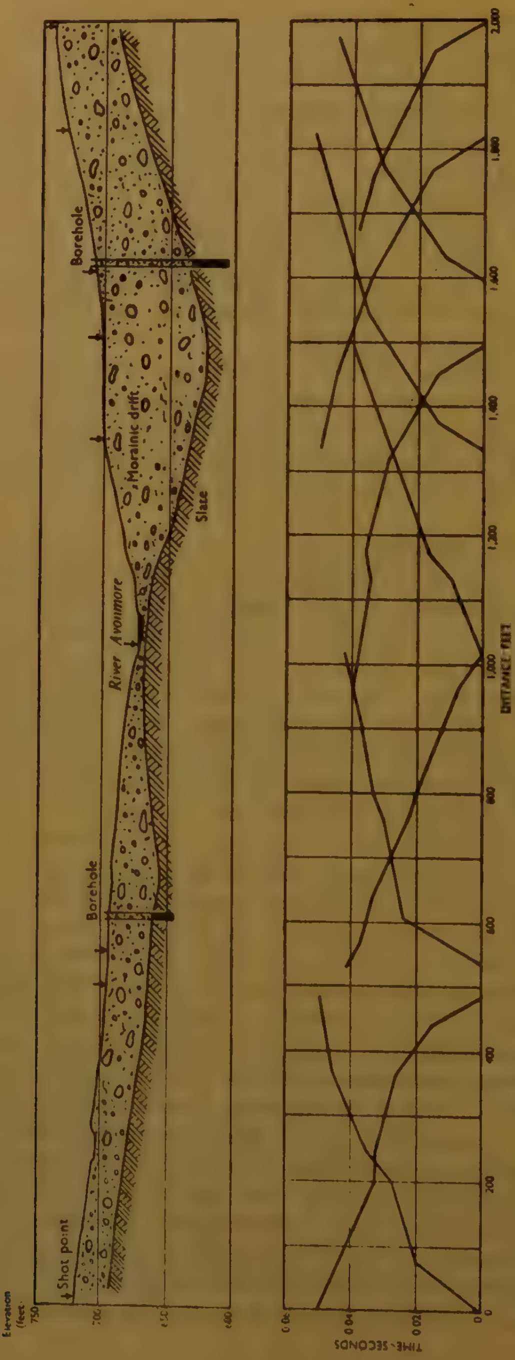


FIG. 19.—SEISMIC SURVEY OF DAM SITE IN EIRE. INTERPRETED ROCK PROFILE ALONG CENTRE-LINE OF DAM AND CORRESPONDING TIME/DISTANCE GRAPHS

The total length of all the sections investigated across the river was 13,000 feet, and the mean error in depth checked by twenty boreholes was less than 6 per cent. Each section took one day to complete and the whole survey was made during the time taken for one drill to complete four boreholes in the river.

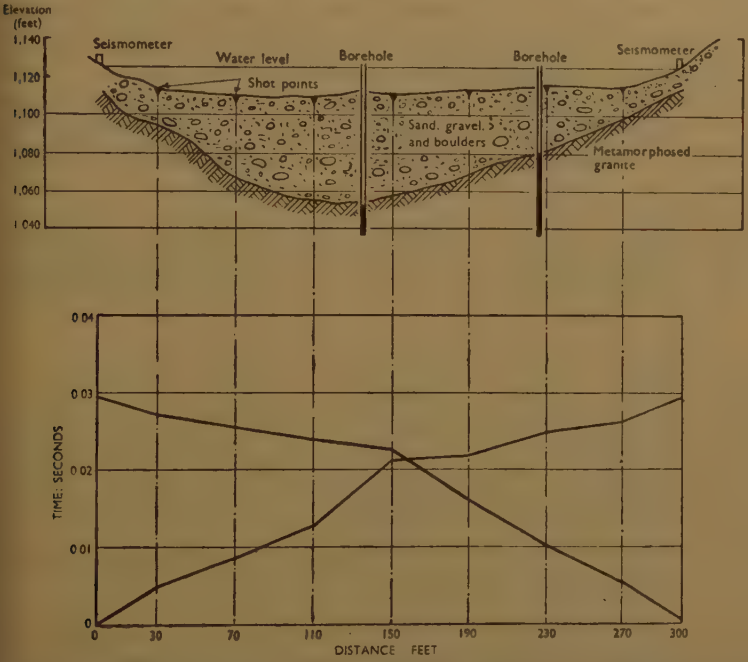


FIG. 21.—SEISMIC SURVEY OF DAM SITE IN PAKISTAN. INTERPRETED ROCK PROFILE ALONG ONE SECTION ACROSS THE RIVER AND CORRESPONDING TIME/DISTANCE GRAPHS

Determination of thickness of superficial deposits overlying the Coal Measures

This example serves to illustrate the interpretation of a seismic survey when an unusual velocity distribution occurs. A survey was made on two adjacent coal mining sites near Wigan, to determine the depth of glacial drift overlying the Coal Measures.[6] The survey formed part of a programme on geophysical prospecting of superficial deposits initiated by the Scientific Department of the National Coal Board. These particular sites were chosen as typical of those in which there might be a danger of break-through from the underlying mine workings into the unconsolidated deposits above, and the object of the investigation was to assess the value of the seismic refraction method under these conditions. One site presented a straightforward three-layer problem, namely, a surface-weathered layer, a layer of glacial drift, and the underlying Coal Measures. The results of one of the traverses on this site are given in Fig. 22 which shows the time/distance graphs and the interpreted geological section. On the second site, however, the results were rather unusual because some of the graphs showed a break in continuity resulting in an apparent time displacement of the latter part of the graphs. These graphs are shown in Fig. 23, and the time displacements are indicated by vertical dotted lines. These unusual results can be caused by an abnorma distribution of velocity with depth. Normally, the velocity of transmission of elastic waves in the ground increases with depth below the surface, each successive layer having a velocity greater than the layer above it If, however, a velocity reversal occurs so that an underlying layer has

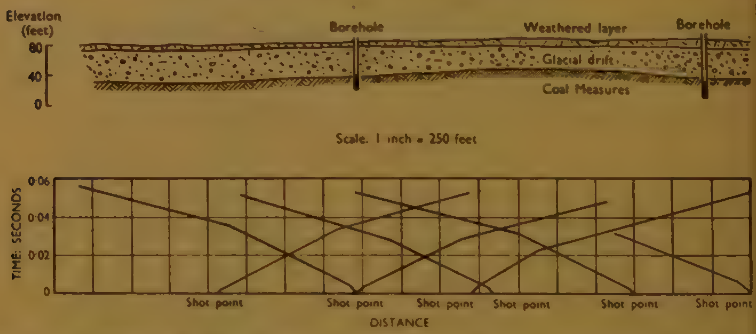


FIG. 22.—SEISMIC SURVEY AT COAL MINE NEAR WIGAN. TIME/DISTANCE GRAPHS AND CORRESPONDING GROUND SECTION

velocity lower than the layer above it, refraction of the elastic waves wi not occur at the boundary of the two layers. Consequently, the lov velocity member would not be represented on the time/distance graph However, refraction will occur at the base of the low velocity layer but if the layer is not very thick, the refraction will be limited to the hig frequency elastic waves only. As the distance from the shot point increases the high frequencies are attenuated, so that a stage will be reache when refraction from the base of the low velocity layer will cease. Subsequent refraction will be from any underlying higher velocity materia in this case, the Coal Measures.

The seismic refraction method is based on the assumption that th velocity of transmission of the elastic waves increases with depth, in whic case the velocities can be determined from the time/distance graphs. I this assumption is not true and a lower velocity layer is present at dept which does not show on the time/distance graph, some allowance has to b made for it in the interpretation. Otherwise, if the interpretation is base only on the high velocities indicated on the curves, the rock depths wi be overestimated. The interpretation of the results on this survey wa based, therefore, on an assumed average value for the velocity in the glacial drift. The velocity taken from the time/distance graphs was 5,500 feet per second, which is clearly the higher velocity in the glacial drift. It was considered probable that the underlying low velocity material would be sandy beds within the glacial drift with a velocity of about 3,500 feet per second. Therefore, a mean velocity throughout the glacial deposits of 4,500 feet per second was used for the interpretation.

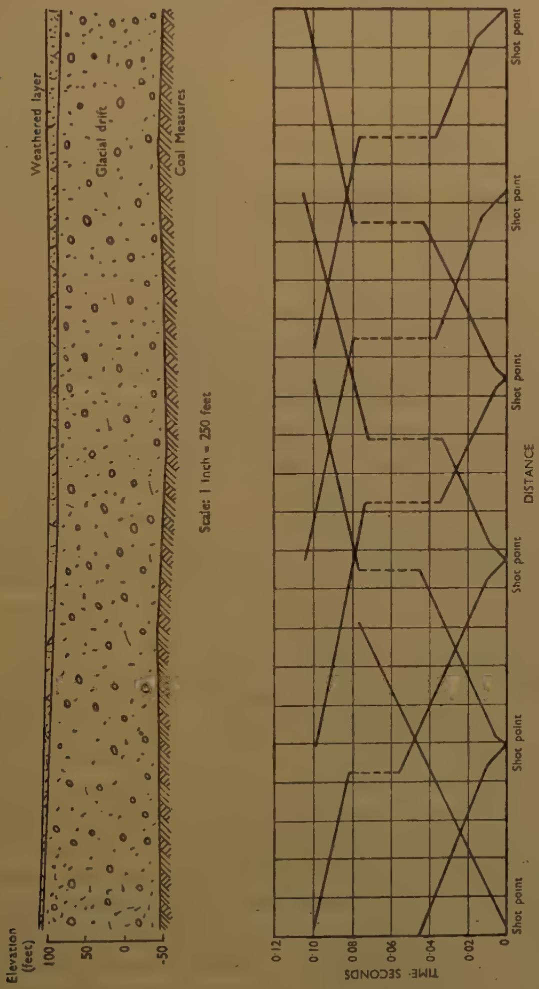


FIG. 23.—SEISMIC SURVEY AT COAL MINE NEAR WIGAN. TIME/DISTANCE GRAPHS AND CORRESPONDING GROUND SECTION

After completion of the interpretation, the results were checked by four boreholes on the site and the results are given in Table 1.

TABLE 1

Borehole No.	Depth to rock by drilling: feet	Depth to rock from seismic results: feet	Error: feet
1	46	48	2
2	57	53	4
3	44	41	3
7	126	133	7

The mean error from these results is 6 per cent which is considered satisfactory since no borehole information was available when the interpretation was made.

Preliminary survey of proposed site for ironworks

This survey was part of a complete site investigation for a proposed ironworks. The survey was of a preliminary nature to determine the approximate bedrock configuration along several traverses across the site with a total length of 12,000 feet. The site was on undulating farm land, and the overburden consisted of boulder clay resting on Coal Measures sandstones and shales.

The survey was made by firing shots at intervals of 120 feet along each traverse with seismometers spaced at 10-foot intervals between them. In order to ensure refraction the seismometer spread from each shot point was usually increased to 240 or 360 feet, as indicated by the length of the time/distance graphs shown in Fig. 24. These are the complete set of time/distance graphs for one traverse across the site. It will be seen that, in most cases, two graphs originate from each shot point. Each graph has three distinct slopes. The first slope represents the velocity of transmission of the elastic waves in the weathered-surface layer, the second slope the velocity in the boulder clay, and the third slope that in the Coal Measures. The velocities and critical distances measured from each graph were used to calculate the depth under each shot point. It will be noted that the third slope on each curve, which represents refraction from the rock, approximates to a straight line. This indicates that there are no rapid changes in the rock depth, and in consequence, the rock profile between each shot point was sketched in with reasonable assurance. The interpreted rock profile is shown above the time/distance graphs in Fig. 24.

The existence of two buried channels beneath the site was indicated by the seismic survey, and confirmed later by borings. From the results of the preliminary seismic survey and nine boreholes, a good picture was obtained of the general rock level throughout the whole site of 150 acres. The survey was completed in two weeks at the rate of 1,000 feet of seismic traverse per day.

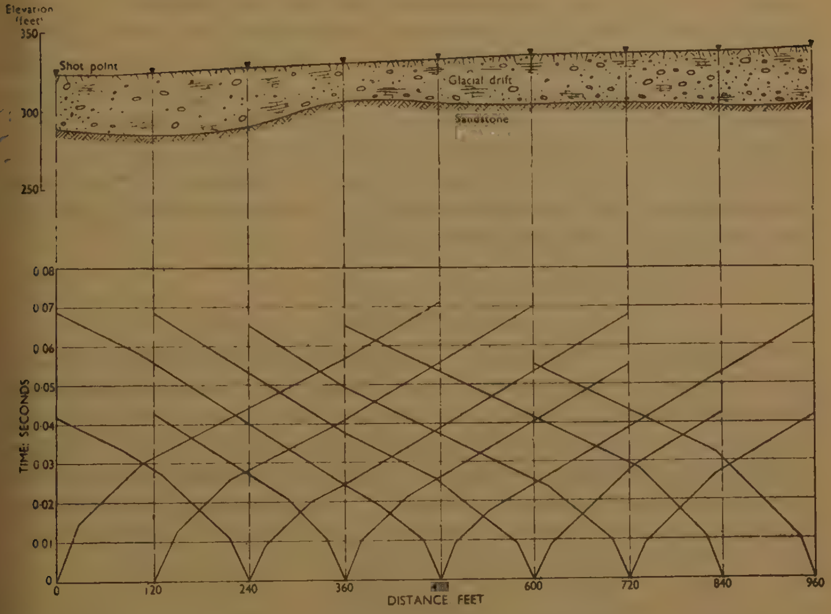


FIG. 24.—SEISMIC SURVEY FOR PROPOSED IRON WORKS. INTERPRETED ROCK PROFILE ALONG A SECTION OF THE SITE AND THE CORRESPONDING TIME/DISTANCE GRAPHS

CONCLUSIONS

The application of geophysical methods to site investigation is a comparatively new technique, and as such is liable to be treated with some suspicion by civil engineers. However, the Authors hope that this Paper has shown that applied geophysics is based on sound physical principles, and when used with discretion can be of appreciable value in a site investigation. The basic theories of the methods are not complicated, and the success of the survey depends largely on the choice of the most suitable method and a valid interpretation. A geophysical survey is not complete without a geological survey. A geological knowledge of the site is essential to select the most suitable geophysical method, and to aid the interpretation.

It is always advisable to correlate the geophysical survey with boreholes on the site.[7] However, it is not essential that the borings be made prior to the survey, because a preliminary interpretation can be made without them. The preliminary interpretation, in fact, enables a more judicious siting of the boreholes with a consequent reduction in the total number of boreholes required.

In general, the seismic method is more accurate than the resistivity method. With a seismic survey and not less than two boreholes, the depth to the bedrock surface can be determined on most sites with sufficient accuracy to meet practical requirements. In the Authors' experience with this method a mean accuracy of 94 per cent has been achieved on depths greater than 20 feet. A similar claim cannot be made for the electrical resistivity method for which the applications are more limited. However, when the geological conditions are favourable, an accuracy of 90 per cent can be expected with the resistivity method and it is undoubtedly quicker and less expensive than the seismic method.

ACKNOWLEDGEMENTS

The Authors are indebted to the Directors of Soil Mechanics Ltd, and Mining and Geophysical Services Ltd, for their co-operation in preparing the Paper. Finally, the Authors wish to thank the following for permission to refer to surveys undertaken on their behalf: Ashmore, Benson, Pease & Co., Binnie, Deacon & Gourley, Electricity Supply Board Eire, Sir William Halcrow & Partners, T. & C. Hawksley, National Coal Board, and Rendel, Palmer & Tritton.

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The Paper, which was received on the 8th April, 1954, is accompanied by six photographs and twenty sheets of drawings, from some o which the half-tone plates and the Figures in the text have been prepared

Discussion

Mr H. J. B. Harding said that, just after world war I several of those present had attended a course of lectures at the Imperial College on oi geology, and had there been told that the liquid oil resources of the worl would be exhausted in 19 years, after which shale oil would be used. The fact that the world was now " swimming in oil " was due to the development of geophysical methods of prospecting. Following their success in mineral and oil exploration those methods had been adapted to civil engineering, though it should be remembered that the problem in civil engineering was very different. In drilling for oil several thousand feet deep, it was far less important to say that the oil was within 600 ft more or less than to say whether there was oil there at all; in civil engineering, however, it was necessary to try to be accurate within a foot, or as near a foot as possible, because even a slight entry into water-bearing silts could make construction an entirely different problem from working in the dry.

After world war II, a certain amount of geophysical work had been done by people who had been carried away by their own enthusiasm. Mr Harding had once previously said at the Institution that among civil engineers wishful thinking amounted to an occupational disease—and that remained true! Consequently, when people had offered results very quickly and very cheaply, there had been an inclination to think that a new magic was available which would solve all the problems almost for nothing.

When the Code of Practice for Site Investigations had been under consideration, various gentlemen interested in geophysics, professors, and others had been asked to give evidence, and some of their claims had been modified. A cautious line had been taken and it had been insisted that wherever possible, or indeed in every case, a geophysical survey should be correlated to boreholes in order to calibrate the findings obtained.

It should be remembered that a geophysical survey proved nothing, but it indicated closely, if carried out by men of experience, what was probably there. The only way to prove what was underground was to go there, either by digging a hole or borehole, or after the excavation had been done.

When the Authors (whom he could not help admitting were colleagues of his) had been first interviewed, they had been examined very closely on their beliefs, and it had been a relief to find that they were extremely modest and reluctant to admit any special claims; on the contrary, they were aware of the difficulties, shortcomings, and possible misinterpretations. It had also been discovered that they were trained civil engineers who had an interest in the matter—not physicists, and so brought a totally different mind to bear when carrying out that work. In their conclusions they stated that the methods " when used with discretion can be of appreciable value in a site investigation." They also stated "A geophysical survey is not complete without a geological survey. A geological knowledge of the site is essential to select the most suitable geophysical method, and to aid the interpretation.

It is always advisable to correlate the geophysical survey with boreholes on the site."

The work which the Authors had done had helped to bring geophysical methods back into their proper sphere, where they could be used with advantage, in the right place, so long as one correlated the geophysical survey with boreholes.

Mr C. M. Roberts said that the last three paragraphs of the Introduction on p. 645 and the beginning of the section headed "Conclusions" on p. 676, to which Mr Harding had referred, appeared to sum up the matter admirably and, provided that the limitations of the method were appreciated, there was little doubt that it could be extremely valuable when used with discretion.

Mr Roberts's own experience covered chiefly the investigation of rock surface underlying peat and drift material in the Highlands of Scotland at comparatively shallow depth, and there was little doubt that that was a very satisfactory function of geophysical methods as applied to civil engineering problems.

In that connexion, he wished to illustrate one example where a geophysical survey could have saved much time and effort.

The example concerned site exploration for the foundations of a dam required to close off a spill-point in a reservoir. A geological report had been obtained but gave no indication of faulting in the region. Borings had later been sunk and appeared to confirm the geological report. However, on excavating the foundations a water-worn gulley had been found crossing the foundations of the dam at right angles to the axis. One of the borings had just missed the lip of the gulley, and a geophysical survey, had it been carried out, would most likely have exposed that fact and led to further borings. Some delay had been caused by the necessity to change the design of that portion of the dam in the region of the gulley during construction.

He thought that that was a good illustration of a case where a geophysical survey would at least have indicated a break in the continuity of the foundation and, if that had appeared, more borings would have been put down.

Just as a few borings were required to check the geophysical survey, so also could the geophysical survey be used to locate further borings in such a way as to gain the maximum information from the minimum number of borings.

Dr W. Bullerwell said that he wished only to amplify some points which the Authors made.

One point had been mentioned by an earlier speaker. In the Paper it was stated that it was important always to correlate the geophysical results to the local geology, and that it was desirable to have calibration boreholes at the end of the survey before the final interpretation of the results was accepted. In Dr Bullerwell's opinion, both those points were extremely well considered and of fundamental importance. A geophysical survey in fact gave indications of the distribution of a physical property within the area, but the association of that physical property with individual beds or formations could only be made with absolute certainty where the geophysical observations and the geological information coincided. Furthermore, because most formations showed a lateral variation in physical properties, though perhaps only on a minor scale, it was generally desirable in a geophysical survey to use the method as a method of interpolation rather than to extrapolate at considerable distances from the geological controls.

He also agreed with the Authors that most check borings were best made after the preliminary interpretation of the results. If that was done, then the check borings could be put down at the points which might be critical to the interpretation of the whole survey, and those points could not be selected until the results had been obtained and an attempt had been made at the interpretation.

On bed-rock problems the Authors claimed a better accuracy for the seismic than for the electrical method. Dr Bullerwell thought that that would generally be conceded. But the electrical methods often could give quickly and economically information sufficiently accurate about the water-table—in fact, in many cases information about the water-table more accurate than was obtainable by the seismic methods. That could be important in civil engineering problems, particularly those connected with sub-surface drainage.

With regard to their choice of methods, he thought the Authors were right in generally disregarding the magnetic and the gravity methods for civil engineering problems. But in connexion with the seismic methods, the Authors described only the refraction method. Dr Bullerwell thought that up to the present it was perfectly true to say that the reflexion method was limited to depths greater than perhaps 400, 500, or 600 ft, but there had been some recent experiments with electro-mechanical seismic sources in which very short travel times had been recorded. The difficulty with the normal seismic reflexion method was that on the trace the very powerful locking impulse or initial impulse from the shot itself, travelling a short distance over the surface, effectively killed the record, so that weak arrivals were lost in the area of disturbance. With the electro-mechanical generator, travel times down to about 50 milliseconds had in fact been recorded, and it seemed that those could possibly be used for investigations of depths of the order of 50 ft and might eventually bring the reflexion method forward as a possible method in civil engineering problems.

Mr K. R. Early said that he was sure that once the principles involved were understood, it would be seen that geophysics was an indispensable aid to many site investigations.

He agreed with Mr Roberts that a particular case where geophysics should always be used was when buried channels were suspected on dam sites.

He was glad that the Authors had stressed the importance of close geological, geophysical, and engineering co-operation in site investigation.

There was one small point which he would criticize ; he always preferred one or two strategic boreholes to be carried out before a geophysical survey. That did not mean a hold-up in continuous boring operations, since geophysical methods were rapid, and a more efficient geophysical survey would result.

Geophysics had been applied to engineering in a number of special ways in addition to the basic applications covered by the Paper. Reference had already been made to their application for the location of underground water supplies, and he would not enlarge upon that. Mention had also been made of their use to locate old buried metallic structures and to find their precise position when the plans had been lost. Another application was in locating old shallow workings which might menace foundations. Most shallow workings in coal-mining districts were old ones the positions of which had been completely lost. In such cases seismic methods could be applied ; they could also be used in the measurement of vibrations affecting structures.

The bulk modulus of elasticity of rocks could be ascertained by measuring the velocity of sound in them. That had been successfully used in the design of high arched dam structures where variations of the modulus in the abutments had to be known.

Research and development of geophysical methods applied to civil engineering were going on so that standard methods were improving and wider applications were being found.

To mention two possibilities ; the first was the use of resistivity to map the clay-content variations of large areas of alluvial desert contemplated for irrigation. In such areas lateral variation in the fluvial deposits might make scattered borings impossible to tie up. The second was the use of the seismic method to determine roughly the permeability of fissured rocks in situ on dam sites.

Mr A. H. Toms described a job which Mr Robertshaw had done for British Railways as an experiment. It had been desired to find the location of a hidden shaft, partly or completely filled in, which was believed to be somewhere under a farm in open country. There were known open shafts near that place and a resistivity survey could be made at the location of the known shafts so that the disturbance of the conductivity of the ground by them could be assessed and related to the resistivity profile over the area where the covered shaft was supposed to be. He thought it was a fair tribute to Mr Robertshaw and his methods to say that the readings he had submitted were, to an engineer, a reasonable indication that in all probability a filled-up shaft did exist in that place in the ground although there was no visible evidence on the surface. That method might be important in certain cases to British Railways, and that was why the test had been made.

There was another job of which Mr Toms had knowledge, although it had been done for another body. A waterworks engineer had asked him for any suggestions as to how water-bearing fissures in the ground might be located. He believed that, following their discussion, a resistivity survey across a slope on the South Downs had enabled water-bearing fissures to be located accurately, but it would not be fair for him to make any other comment than that.

Those were the only occasions on which he had been associated with resistivity surveys, and he had reason to believe that in both cases they had been able to give a satisfactory answer.

Mr R. C. Harvey said that one of the investigations described in the Paper and undertaken by the geophysicists had been for a client of his firm—and there was an aspect of the matter which he thought might be of some interest to certain civil engineers, particularly consultants. That aspect concerned the contractual side. The job in question had been abroad, and it had been originally arranged that the geophysical survey should be carried out by a Continental firm of specialists. The firm had submitted quite a good offer for the job, although it was very expensive, but the conditions had been very trying. One of the conditions had been that there should be prior payment of the whole estimated cost of the survey into a bank in Europe by means of an irrevocable letter-of-credit against which the firm would draw their payments as they considered them due. That method, by the way, was very common with American contractors, many of whom had their money in a bank in New York before they set foot in or cut a sod in a foreign country. He thought that probably they were changing their methods now as a result of competition, but that sort of thing was not uncommon.

To the government concerned that condition had not been acceptable. There had also been other rather irksome conditions in the proposal to which objection had been taken. The specialists had declined to change their offer and, after some protracted negotiations, the government had decided not to accept it. They had expressed their great displeasure with the foreign people concerned and things were more or less at stalemate for quite a while.

At that time Mr Harvey went abroad for his firm and he had had the job of trying to placate the client and of getting somebody to do that particular job. He had suggested that the method of payment should be changed. The solution was, of course, simple and was that the specialist contractors would be paid on the certificate of the consulting engineer. That had been acceptable to the client and also, he thought, very acceptable to the specialists. It had taken rather a long time to fix the details, and he believed that it was nearly 12 months before the geophysicists actually arrived to do the work, but the work itself was very quickly done. That difficulty was a feature which could affect such work when it was carried out abroad, and it meant that the specialist sometimes wanted the help of the consultant.

Another aspect was the conditions for getting geophysicists and their expensive equipment into a country and out of it without the business costing them a great deal of money. Many of those countries, particularly the eastern countries, which were now more or less emancipated, had difficult customs regulations which did not always work very promptly. Moreover, they also had rigid export controls. Unless one was very careful and organized matters properly beforehand, it was quite possible for a geophysicist to have to pay a lot of customs duty on going into, and then not be allowed to take his equipment out of a country. That might appear to be a small point, but it was of some importance in connexion with some works abroad.

Mr Jack Duvivier asked whether the Authors would care to comment on the application of geophysical methods of investigation to a problem which had been put to his firm a short time ago, namely, to determine the depth of unconsolidated material overlying the bed-rock on the sea-bed some miles offshore with a view to determining the distance to which underground colliery workings might be extended out to sea.

Mr Julius Kennard stated that he had had two experiences of the use of geophysical methods, one in connexion with the selection of a line for a wing trench for a dam, and the other in connexion with the choosing of a site for a well in chalk. On both occasions the results had been very satisfactory from the point of view of providing him with the information required, but there was no doubt that the reliable interpretation of the results obtained from a resistivity survey must depend on the experience of the investigator. In the latter case it was true to say that the site suggested was an excellent one from a water-bearing aspect, but it was subsequently found impossible to proceed with the sinking of a large-diameter well owing to the fact that the chalk was so full of water that it was almost in the nature of slurry. Instead of a well, two boreholes were drilled, each surrounded by a gravel screen.

He thought that the members would very much like the Authors to give some information regarding the costs of typical geophysical surveys.

Mr P. D. Brown, in reply, said that judging from the comments made the Authors had achieved their aim in presenting the Paper, namely, to try to demonstrate to the civil engineering profession that there was an application for geophysical methods in civil engineering, provided that those methods were used with discretion and correlated with the known geology of the area.

Mr Harding had mentioned geophysical exploration in the oilfields and had made the point that, since the depth was so great, an error of a few hundred feet did not really matter; the information obtained could still be of great value, but in civil engineering with very much shallower depths more detail was essential. It was for that reason, perhaps, that the application of geophysical methods to civil engineering problems had been so slow. It had been necessary to wait for the development of new and more sensitive equipment; and still it was not an easy problem always to interpret the results on those shallow problems to obtain the detail required. The work for oil exploration was certainly more spectacular and far more costly, of course, but Mr Brown thought that the application of geophysical methods to engineering was none the less useful.

Mr Roberts had mentioned the problem of the deep gully. That would have been an excellent problem for a resistivity survey, provided that the overburden was reasonably uniform in its composition. In saying that, he (Mr Brown) did not mean that the overburden needed to consist entirely of one material such as clay or sand; he meant uniform in the mass, as for example a reasonably uniform mixture of clay and sand and gravel, and not a large part of clay in one place or sand or gravel in other places. That sort of thing would make a resistivity survey useless. Provided that the overburden was a reasonably uniform material, a resistivity survey across the valley would have produced a definite anomaly over the gully. He did not know how wide the valley was; but assuming that it was not more than half a mile wide, it would have been possible to run three or four profiles across the valley in about 3 days at a cost of about £100.

The question whether boreholes should be put down before or after the geophysical survey had been raised by Dr Bullerwell and Mr Early. Mr Brown thought that the answer was that in the case of very large sites, as for example the site for a hydro-electric scheme, it would be preferable to have a couple of boreholes put down first. Since there would be a lot of drilling done any way, it was as well to start the boring programme first or perhaps at the same time as the geophysical survey so that the results of two boreholes would be available before the geophysical survey was finished. On the other hand, on a very small site where, with the aid of geophysical methods, one hoped there would not have to be more than two or three boreholes, he thought it was better to do the geophysical survey first so that the boreholes could be placed where they would give the most useful information.

The question of locating old coal workings or shafts and tunnels had been raised in the discussion. The Authors had done a number of surveys for that purpose. Their experience was that it was very difficult to decide from theoretical considerations whether or not the survey would be successful, and that the only way to find out was in fact by doing a test survey over some known pit or cavity or whatever it was one was looking for. On some jobs the Authors had felt before doing them that there was very little hope of getting any results, but then they had been able to locate those old workings or tunnels and had got remarkably good results. Those successes could not be explained theoretically. On other occasions when the Authors had been fairly confident beforehand and there had been every reason to believe that they would be able to detect the old workings they had failed to do so. Usually the failure had resulted from other variations in the ground which were producing geophysical anomalies similar to the anomalies which were expected over old workings, and it had sometimes not been possible to differentiate between one anomaly or another. It was not there a question so much of geology; one was looking for man-made things.

A question had been asked about the cost of geophysical surveys. It was very difficult to generalize, but he would give some figures to indicate the lines the costs followed. For a resistivity survey in the case of large areas (exceeding 100 acres), using the lateral traversing method described in the Paper and covering the ground in reasonable detail, the cost would be of the order of 30*s* 0*d* an acre. On the other hand, for very small areas of a few acres, a similar survey would cost at least £10 to £20 an acre. In other words, on a very small area a geophysical survey might become uneconomic. In the case of running resistivity profiles along tunnel lines or proposed road routes, a resistivity survey would cost something like £20 to £50 per mile of traverse. In the case of seismic surveys—the seismic methods being principally used for depth determinations—for the profile shooting which was the main method described in the Paper the cost was something like £100 to £120 per thousand feet of profile. It was far more expensive than the resistivity method; on the other hand, it could be used on many occasions when the resistivity method would be quite unsuitable. A cost of £100 or £120 per thousand feet might sound a lot at first, but if there was rather a large variation in the rock profile it would cost very much more to get that profile entirely by means of borings. Obviously some borings were needed, but by using the seismic method to profile between widely spaced boreholes, using the boreholes as control on the interpretation, the rock profile could be determined reasonably cheaply.

Mr J. Robertshaw, in reply, said that Mr Harding, Mr Roberts and Mr Early had mentioned the need for confirmatory boreholes. That, of course, had been emphasized in the Paper. The question seemed to be when those boreholes should be put down. From experience, the Authors had found that usually they had very little say in the matter. Either the boreholes had already been put down before they went on to the site or before they were even asked to do a survey, or for one reason or another the borings could not be put down until after the survey was done. However, borings were essential and should be put down.

Mr Early had pointed out other applications of geophysical methods—for example, in the location of old mine workings, to which Mr Brown had already referred in his reply. The use of the resistivity method for doing soil surveys where one was interested in the permeable nature of the soil for irrigation had also been mentioned. Although the Authors had not undertaken that type of work, there seemed no reason why that method should not be used to tie in between widely spaced boreholes.

Mr Toms had mentioned as an example a survey which the Authors had done to locate an old constructional shaft above a railway tunnel. Actually that had been in the nature of a trial survey to see if there was any possibility of locating those constructional shafts which, on occasions, did cause trouble owing to seepage down them into the tunnel below. The site for the trial had been chosen very carefully, because it was very important when looking for comparatively small features such as a filled-in constructional shaft that there should be no great variation in the local geology. In that case the material over the tunnel was Wadhurst clay, which was very consistent throughout. The shaft had been filled with sandstone from the tunnel, and consequently there had been an appreciable contrast in the electrical properties of the sandstone fill and the surrounding Wadhurst clay.

Mr Harvey had referred to overseas geophysical work. In that respect Mr Robertshaw felt that geophysics could be of great value. On a number of occasions the Authors had undertaken overseas work, and from experience had found they could be on a site within a few weeks of being asked to start, complete with their equipment; whereas if one had to resort to an immediate boring programme it might be several months before the equipment would reach the site. Therefore, since time was often of great importance on overseas work, geophysical methods could be of great assistance. By that he did not mean that boreholes were not needed—they certainly were, but at least an initial geophysical survey might give sufficient information to enable some preliminary calculations and design.

On the question of costs, one point that he would like to add to Mr Brown's reply was that the cost was not always important. For instance, in connexion with the problem which Mr Roberts had raised, he was quite sure that Mr Roberts would have spent quite happily a few hundred pounds to have found that hidden channel. In such a case the cost was not the vital factor; the important thing was to be able to find the channel, and obviously, unless one peppered the site with boreholes, it would be almost impossible to locate a feature of that nature.

With regard to undertaking geophysics at sea, quite a lot of work was already being done in the Persian Gulf by oil companies. There was no problem technically in undertaking geophysics over water. The only difficulties were in being able to locate oneself accurately at sea, and coping with tidal conditions. Apart from that, there was no reason whatever why the problem suggested by Mr Duvivier should not be undertaken.

Correspondence

Mr E. S. Boniface (Deputy Supply Engineer, Metropolitan Wate Board) asked for the Authors' comments on the value of electrica resistivity methods to determine the best position to sink a well. He understood that it was difficult to establish the layout of forgotte underground workings above the water-table using that method and possibly, more difficult to find such workings if they were flooded. In one case he knew an electrical resistivity survey, by experienced geophysicists for water-supply purposes, had failed to show the presence of a considerabl length of heading driven through the Chalk about 100 ft below the surface The overburden at the site consisted of a total of about 30 ft of alluvium and Thanet Sand.

He felt that a sense of proportion was essential in assessing the value o geophysical explorations. The methods were not yet refined enough t show where large water-bearing fissures existed in a stratum such as the Chalk, and Mr Boniface would be glad of the Authors' opinion on the possibility of improvement in technique to a point where such refinemen was possible. In the Chalk it was of little interest to the water engineer seeking large supplies, to know that in one area the Chalk mass was more porous than in another, for porosity values might, or might not, indicat the presence of fissures. What the engineer wanted was a comparison between permeability values.

Mr B. G. Fish (Head of the Drilling and Breaking-down Group National Coal Board's Central Research Establishment II, Isleworth said that he had been concerned with the organization of a research programme on the use of geophysics in the survey of superficial deposit overlying coal-mine workings, and had collaborated with the Authors on one of the surveys they described.

The survey of the depth of superficial deposits was essentially a problem of determining the thickness of unconsolidated material overlying bedrock That was not difficult to do by drilling, but where accuracy was required or where rapid changes in slope of the sub-surface feature were involved the number of holes necessary to achieve a satisfactory solution could become very great. Geophysical aids would therefore stand or fall by thei savings in time and money.

For the National Coal Board programme both resistivity and seismi teams were used. His own conclusion, based on the results of investigations at a variety of sites, was that the resistivity method was rathe selective and could give misleading results where undetected random changes occurred in the resistivity characteristics of the deposits involved

A good deal had to be known about the site beforehand if the best technique was to be quickly established. In addition, interpretation of field data could be very hazardous.

Although more expensive to apply on an organized basis (because specialist staff were needed and shot-holes had to be drilled and flushing water provided), the seismic refraction method gave more positive results. There was no wide range in methods of application requiring selection ; the only requirement was a reasonable velocity contrast at the feature under study.

In a given site, whatever geophysical method was adopted, an economic compromise would be needed between the benefits of rapid and continuous profiling and the additional cost compared with the normally slower drilling method. It was clear that there would be many surveys in which geophysics could usefully be invoked to give a general sub-surface picture ; that would then need to be confirmed from point to point by occasional boreholes.

He thought that the seismic method would be more generally applicable, other things being equal, because of less likelihood of lateral variation in velocity characteristics compared with resistivity characteristics in a given bed. Did the Authors agree ?

Mr K. N. Engel observed that certain important variations of the methods described could have merited inclusion. Some of the mathematical premises from which the Authors appeared to derive their results seemed erroneous.

The only electrode configuration mentioned was the Wenner configuration—admittedly the most widely used—where the four electrodes were equidistant and in line, thus reducing calculations to their simplest form. Judicially applied, however, other configurations could give greater accuracy for the tracing of vertical features such as faults, dykes, buried channels, etc., and five-electrode configurations were sometimes employed for dip determinations.

Perhaps it might be suggested that with growing experience better results could be achieved in interpretation of resistivity diagrams with less adherence to curve-fitting methods. That would, of course, introduce bias into the interpretation, but bias influenced by a knowledge of the cumulative resistivity curves, the general geology of the area, site conditions, and factors affecting individual measurements, could lead to " weighted " and therefore " better than random " results.

The curves of the time/distance graph in Fig. 13 were lettered as if the seismic velocity in the rock was different in an up-dip and a down-dip shot. The Authors explained that the slopes were a function of both the velocity through the rock and the angle of dip. They did not mention that a third determining factor was the seismic velocity of the upper layer. (It should also be noted that all those slopes were expressions of the *reciprocal* of the velocities, true, or apparent.) That, of course, robbed the graphic solution in Fig. 14 of its legitimacy, except as an approximation.

In other words, if the *apparent* up-dip velocity in the bedrock was V_{2n} and the *apparent* down-dip velocity V_{2d} (taking apparent to mean "as it would appear from the curve in the diagram") then, for an angle of dip of θ the corresponding slopes would be: $1/V_{2n}$ and $1/V_{2d}$ where $1/V_{2n} = 1/V_1 \sin(i - \theta)$ and $1/V_{2d} = 1/V_1 \sin(i + \theta)$, but, as mentioned in the Paper, $\sin i = V_1/V_2$ so that V_{2n} and V_{2d} were completely defined by V_1, V_2, and θ.

The true seismic velocity of the bedrock, V_2, was given by the expression:

$$V_2 = \frac{2 \cos \theta}{\dfrac{1}{V_{2d}} + \dfrac{1}{V_{2n}}}$$

It would be seen that as θ became small and $\cos \theta$ approached unity, V_2 was close to the average of V_{2d} and V_{2n}. In such cases that could be used as a first approximation.

The depth Z to the dipping interface was given by:

$$Z = x \tan \theta + \frac{T_{od}\,(V_{2d} + V_{2n})}{V_{2d}V_{2n}} \tan i$$

where x denoted the distance from shotpoint A to the point for which the depth was being measured and T_{od} was the length of the time axis of the graph from its origin to the point of intersection with a backward extrapolation of the second part of the down-dip shot time/distance curve.

Since in nature the interface could, at best, only approximate to the ideal plane of that theoretical treatment, that result would evidently be most accurate for Z when x was chosen to be approximately half the value of the distance between shotpoint A and the point corresponding to the critical turning point of the curve where the first arrival was the refracted wave.

Furthermore, the depth determination was always made for a point which had necessarily to be away from the shotpoint and not for the shotpoint itself as stated in the Paper.

It was perhaps unfortunate that the Authors made no mention of recent developments in the use of other sources of seismic energy than explosives, such as impact caused by the dropping of a heavy weight, which was likely to be of great interest to the civil engineer, who was often concerned with areas where the use of explosives was not permissible, or might be undesirable for a variety of reasons. It was precisely in the relatively shallow operations of site investigation (as against the deep oil prospecting) that those methods could be most effective. Methods on those lines were being perfected by a survey company in South Africa, by several geophysical companies in the United States, and by one in Britain.

Because in that type of seismic survey only the first arrival wave entered the calculations, modern apparatus was sometimes constructed to measure only that first arrival time, and by omitting to produce the full records of subsequent seismic arrivals, a further saving in weight of equipment could be made.

The Authors, in reply, agreed with Mr Boniface that it was not always possible to locate underground workings by geophysical methods. Such workings had to be of a reasonable size in comparison with their depth in order to be located with certainty. If possible a test should be made over known workings in the locality. If the test was successful the survey could then be extended over the area under investigation. If any old workings were then suspected as a result of the survey they should be proved finally by borings. The heading referred to by Mr Boniface had presumably been filled with water, and it was possible that the water might have a similar resistivity to that of the surrounding water-bearing chalk. Under such circumstances there would be little chance of locating its position by the resistivity method at that depth.

The resistivity of chalk depended mainly on its moisture content, and therefore fissured zones normally had a low resistivity. Those low-resistivity areas could usually be detected by the lateral traversing technique. If a borehole was put down in that low-resistivity area it might not strike the major fissure, but in all probability it would enable water to be drawn from it. Mr Boniface might be interested to learn that geophysical methods had been used extensively by the Royal Engineers during the 1939–45 war to locate water supplies in the Middle East, often in limestone and chalk formations. The methods used and the results were given in Military Engineering, Volume VI, Supplement No. 1, published by the War Office.

The Authors agreed with Mr Fish that the seismic refraction method was more suitable than the resistivity method in determining the thickness of superficial deposits over the Coal Measures. Appreciable variations occurred in the nature of those superficial deposits. The variations could be detected in the seismic method by changes in the velocity, and due allowance could therefore be made in interpreting the depth to the Coal Measures. However, with the resistivity method the accuracy depended on the superficial deposits being reasonably homogeneous, and any appreciable variations made the method unreliable.

It would seem very desirable that geophysical surveys should be made in areas of the National Coal Board where buried channels occurred, and shallow seams were being worked. Such buried channels could be located with reasonable certainty by a seismic survey between widely spaced boreholes.

Mr Fish had made passing reference to the drilling of shotholes, and in that connexion the Authors mentioned that power-operated drills and flushing works were not required for drilling shotholes for seismic investigations except at depths exceeding 200 ft. A simple hand auger was normally adequate for making the shallow shotholes required when profiling the surface of the bedrock by seismic methods.

The Authors agreed with Mr Engel that the Wenner electrode configuration was the most commonly used system in resistivity surveying and in their experience they had found it to be more reliable than the many other configurations. They agreed also with Mr Engel, and had stressed in the Paper, that a study of the geology of the area was essential when interpreting geophysical data. The cumulative method of interpreting resistivity curves was of course only an empirical method, but as such it was sometimes useful as a check on the more satisfactory curve-analysis method.

They would point out to Mr Engel that the main purpose of the Paper was to demonstrate the practical applications and limitations of established geophysical methods to civil engineering problems. They had purposely avoided mathematics in the Paper for they felt it would detract from the general interest. The theoretical aspect of applied geophysics, including the equations presented by Mr Engel, was adequately covered in references 2 and 3, given at the end of the Paper.

They suggested that a better approximation for the true rock velocity in the case of a dipping bedrock surface was given by $2\frac{V_{2d} \cdot V_{2n}}{V_{2d} + V_{2n}}$. On engineering sites where there was usually a velocity contrast of about 2 to 1, that approximation was in error by $3\frac{1}{2}\%$ for a dip of 15°. The error was close to the accuracy with which the bedrock velocity could be measured. The approximation suggested by Mr Engel would be in error by 32%.

It was not usually adequate on engineering sites to determine only one depth for each geophone spread. Information was required in much greater detail and the depth had to be established for each geophone at which refraction occurred. For an irregular bedrock surface that could be accomplished only by some graphical method such as described in the Paper, for no practical mathematical treatment was possible.

The Authors had carried out field tests about 4 years ago using a dropping weight as a source of seismic energy. A 100-lb. weight had been dropped about 6 ft from a light-alloy frame using a quick-release mechanism. It produced a little less energy than $\frac{1}{2}$ lb. of gelignite which would be adequate for most site investigations. However, small explosive charges were very much more convenient to use than the heavy drop-weight apparatus, and contrary to Mr Engel's belief, there were few engineering sites where the use of small explosive charges was not permissible. Fortunately in the Authors' 10 years' experience they have not encountered such a site.

JOINT MEETING WITH THE INSTITUTION OF MECHANICAL ENGINEERS AND THE INSTITUTION OF ELECTRICAL ENGINEERS

Wednesday, 4 May, 1955

Mr David M. Watson, President of the Institution of Civil Engineers, who took the Chair at the commencement of the meeting, explained that it was a Joint Meeting of the Institution of Civil Engineers, the Institution of Mechanical Engineers, and the Institution of Electrical Engineers, and it was customary when two or more of the Institutions met in a Joint Meeting for the President of one of the visiting Institutions to be invited to take the Chair. He had very great pleasure in asking the President of the Institution of Mechanical Engineers, Mr P. L. Jones, to take the Chair.

Mr P. L. Jones then took the Chair. He thanked Mr Watson for inviting him to take the Chair, which he regarded as a very great compliment.

The Chairman said that the members of the three Institutions who were present valued the opportunity of a Joint Meeting to listen to the first Graham Clark Lecture, which was to be given by Sir Harold Hartley. It was the first of a series of lectures which would be of great educational value year by year.

The Councils of the three Institutions had had in mind for some time the establishment of an annual lecture which would deal with a subject of wide engineering interest and thereby have an appeal to all of their members. Mr Graham Clark had been vitally interested in the preliminary discussions on the project, and he it was who had suggested that, so far as was possible, each lecture should have some cultural content in addition to being of technical value. Personally, the Chairman felt it was very appropriate that Mr Graham Clark's name should be linked with the lectures, and it was also very satisfying that the first of the series should be held in the building with which Mr Graham Clark had been so closely associated for so many years.

Sir Harold Hartley needed no introduction to engineers; they were very grateful to him for coming.

The Chairman then asked Sir Harold to deliver the first Graham Clark Lecture, the subject being "The Engineer's Contribution to the Conservation of Natural Resources."

Sir Harold Hartley then delivered the following Lecture.

THE GRAHAM CLARK LECTURE, 1955

THE ENGINEER'S CONTRIBUTION TO THE CONSERVATION OF NATURAL RESOURCES

by

Sir Harold Hartley, K.C.V.O., C.B.E., M.C., D.C.L., F.R.S.

It is my privilege this afternoon to give the first Graham Clark Lecture and it is appropriate, that I should begin by paying a tribute to the man whom these lectures commemorate and whose idea they were. I first met Graham Clark when I gave the James Forrest Lecture in 1933 and from then onwards like so many of you I had to thank him for constant acts of kindness and courtesy. The Secretaries of the Institutions, if they are wise, can exert great influence on policy, and this was certainly true of Graham Clark. But apart from all he did for the well-being of his own Institution for 17 years as Secretary, his most important contribution was his insistence on the essential unity of the engineering profession. He saw so clearly that with the inevitable increase of specialization there was an increasing need to secure a common understanding and sympathy, as any great engineering work was bound to be a combined operation. This is an aspect to which I shall return in my lecture more than once. And as a means of fostering this mutual understanding Graham Clark suggested these lectures on subjects of common interest to the three Institutions. As for 15 years it was my own task to co-ordinate the work of civil, mechanical, electrical, marine, signal, and road motor engineers and provide them with a common research service, I share his point of view.

Graham Clark was constantly thinking out means of strengthening the bonds between the Institutions and of forging new links with the engineers of other countries. With the experience of the war he and his colleagues set out to form the Commonwealth body which first met in 1946. A year later, taking advantage of the proposals of the second oldest engineering body in the world—the Royal Dutch Institution—they embarked on the formation of the European and American Conference, when Graham Clark's fluent knowledge of French was of great assistance. Those are some of his constructive contributions which this lecture is meant to keep in mind.

The scope of the lecture

When I came to consider the title of this lecture I was faced with a certain dilemma, for it is the ingenuity and initiative of the engineer in satisfying the growing demands of the world by new inventions and revolutionizing our way of living, which have stepped up the consumption of natural resources so that the ever-growing inroads upon them have now become a matter of serious concern. In 1828 Thomas Tredgold defined engineering as " the art of directing the sources of power of Nature for the use and convenience of man." That still stands today if for " sources of power " we substitute the word in my title " resources," bearing in mind that since 1828 the profession of engineer has been continuously extended to include, besides civil engineering, mechanical, electrical, and chemical engineering and all the other technologies which today administer to the comfort and well-being of mankind. I shall therefore interpret my title in the widest sense to include all these engineering technologies as it is the intention of these lectures to commemorate the wide outlook of Graham Clark himself and his wish to see the Institutions co-operating on broad lines of policy. How am I to reconcile the idea of conservation with the steadily increasing consumption by the engineer of the world's natural resources ?

Now conservation is defined in the Oxford dictionary as " preservation from destructive influences, decay or waste." Leaving aside for the moment the raw materials which are the basis of all engineering production, let me ask what are the natural resources on which civilization has been built and which today are proving the limiting factors both in development and in supplying the world's food, its most crying need ? The answer is soil and water. It is here from the earliest times that the engineer has made his basic contribution to the conservation of resources, and the material future of the world is so largely dependent on his continuous success in this field.

Water and the irrigation engineer

Water I put first as it is essential to all forms of life and industry. You may remember the words of Robert Browning standing at the window of his palace on the Grand Canal at Venice when a total abstainer was extolling the virtues of water. " Water," said Browning, " as you see, for purposes of locomotion most convenient, for washing indispensable, but to drink, God forbid." Be that as it may, water is proving more and more to be the indispensable resource on which plans so often have to be based and its conservation has the highest priority. Without it soil becomes a desert, production an impossibility but water is also a potent source of destruction and a carrier of disease, so the engineer has here a dual task.

We are dependent for fresh water on rainfall, on lakes, rivers and springs, on underground and man-made reservoirs, and for salt water on the sea. Thanks to the sun's radiation there is a continuous cycle of evaporation and rainfall; 98% of the earth's water is in the sea, 98% of the rest is frozen in the polar ice caps, only 0·04% of the water is in the rivers and lakes, and only one part in 100,000 in the hydrologic cycle in the atmosphere on which life depends. The formation of soil is dependent on the weathering action of water and ice on the rocks, some soils are wind-blown but most are formed by waterborne alluvium. That is the raw material on which in prehistoric times the living assemblage which constitutes fertile soil developed, with its vast population of micro-organisms, fungi, algae, protozoa and bacteria, of which there are many millions in a gram of soil. Then nature took a hand in conserving this precious material with her forests on the slopes with their deep roots to absorb and hold the water and protect the soil against the run-off. On the plains, the prairies and pampas of North and South America, grass held the soil and gave it permanence. The coming of man, his interference with nature's conservation, the felling of the trees and the ploughing of the plains made problems for the engineer to grapple with.

What was the engineer's contribution in the oldest centres of civilization? They were not situated in the temperate zone with its kindly rainfall but in the rainless semi-arid zones of Mesopotamia and Egypt and their existence was dependent on the irrigation engineer. It was the early skill of the irrigation engineer that made possible the temples and pyramids of Egypt and the hanging gardens of Babylon. In Egypt irrigation dates from the Old Kingdom, possibly as early as 3000 B.C., when embankments were built partly as a flood protection and partly to form a reservoir. From this developed a system of basin irrigation from the Nile flood with terraced basins all the way from Aswan to the sea. In Mesopotamia the Sumerians fertilized their fields by irrigation trenches as early as 5000 B.C. and there is an inscription recording the irrigation schemes of Hammurabi the founder of the Babylonian Empire in the year 2000 B.C. The fertility of Babylonia became a source of envy and astonishment to the Greeks. Later Sennacherib built a great aqueduct 50 miles long to bring water to Nineveh and to irrigate the orchards and gardens outside the city wall. It was as wide as an arterial road and paved with masonry; a dam with sluice gates regulated the flow and enabled water to be stored. These early irrigation engineers were most skilful in the design and control of their large canal systems. Some like the Nahrwan Canal running for 200 miles parallel with the Tigris rivalled the largest modern works in their boldness of conception. They knew how to divert rivers by dams and to dig great artificial canals to lead the rivers into their irrigation systems and to avoid the risks of erosion and silt.

The great cities like Ur of the Chaldees were dependent on water and when the Euphrates shifted its course and the network of irrigation canals was emptied, Ur was abandoned and left to become the impressive heap of ruins we fly over today. Others like Babylon, Nineveh, and Ctesiphon were more fortunate and their irrigation systems continued as the basis of their fertility and wealth until the 13th century when they were destroyed by the Mongol invaders and Mesopotamia became a land of ruins and desolation through which great waters ran to waste or overflowed their banks to make malarial swamps.

In the Roman Empire water was carried in great aqueducts on arches wherever it was needed, and when an aqueduct had to cross a valley on tiers of arches, like the Pont du Gard at Nimes, their relative positions were structurally correct. I well remember the first time I realized what water meant to man. After a long ride on an obstinate mule through the sandy foothills of the northern range of mountains in Cyprus, we suddenly came over a rise to the village of Kythraea with its beautiful orchards in full bloom. We sat down to eat lunch at a great spring, the source of that fertility, and across the plain of the Mesaoria one could trace the abutments of the aqueduct that carried that water to Salamis in the days when St Paul landed there. The aqueduct has perished and Salamis is a wilderness of wattle.

In India the Mogul Emperors extended the irrigation schemes of their predecessors in the arid plains of the Indus and Ganges but their declining empire was unequal to the maintenance and administration of the complex system and so the canals became choked with silt and fell into disuse until the coming of the British in the 19th century and the rebirth of irrigation engineering. By 1830 the engineers of the East India Company had reopened the old Delhi and Jumna canals in the North and were improving the ancient irrigation works in the Cauvery Delta in the South. Many lessons were learnt of the behaviour of water and the problems of scour and silt, and when the famine of 1832 had intensified the need for more water, Proby Cautley in the North and Arthur Cotton in the South, two great pioneers, were able to embark on the great projects which laid the foundation of modern irrigation engineering. Cautley's 300 mile Ganges Canal with its great Solani aqueduct still ranks as one of the major irrigation schemes of the world. Then followed a long series of hydraulic projects all over India which increased greatly the area of fertile land and provided the experience on which later developments in Egypt and Mesopotamia and other parts of the world were based.

The multiple-purpose water schemes

Meanwhile the advent of hydro-electric power and the advance in engineering techniques made possible the multi-purpose schemes for water control with their objectives of flood control, power supply, irrigation, and transport.

The Tennessee Valley with its twenty-seven dams and reservoirs controlling a river basin of 40,000 sq. miles is one of the most comprehensive of these schemes and has been completed long enough to justify what was claimed for it. The valley has an ample rainfall so the objectives were flood control, power, and communications. The reservoirs provide 11½ million acre-feet of storage for flood control at the beginning of the flood season and have saved an immense amount of flood damage each year. Six million acres of rich bottomland is protected in this way. The replanting of the slopes has stopped soil erosion, has made the muddy streams clear again and delayed the silting of the reservoirs. T.V.A. brought new life into a depressed area and did much to raise its standard of living.

The great dams and reservoirs on the American rivers flowing to the West like Grand Coulee, Shasta, and the Hoover Dam are more spectacular and serve the additional purpose of the irrigation of millions of acres of rich agricultural land.

In Canada, the Kemano-Kitimat project came into operation last year. In this a string of rivers and lakes has been dammed into a 150-mile reservoir and the flow of water diverted from east to west. The backed-up water then drops through a 10-mile tunnel in the mountains to the power station at Kemano which has a capacity of 330,000 kW. This will be increased later to 1·7 million kW. The power is transmitted 49 miles to Kitimat, where it is used in the aluminium smelter.

Similar schemes with the same objectives are going forward in many other parts of the world. It is interesting that the first major arch dam to be designed by British engineers is on a tributary of the Tigris, the earliest home of irrigation. The Dokan Dam on the Lesser Zab river now under construction will help to control the floods of the Tigris and with a subsidiary barrage will provide irrigation for 2,000 sq. miles of desert area. It will have a storage capacity of about 5 million acre-feet and a hydro-electric power potential of 143,000 kW.

In Africa there are the Volta River and the Shire Valley projects. On the Volta River there are no substantial falls to facilitate the production of hydro-electric power so the scheme takes the form of a large rockfill dam over 300 ft high across the river at Ajena which would impound an artificial lake of some 3,000 sq. miles in area and 300 miles in length. The head is entirely that produced by the dam itself and the power station would provide an average output of 580,000 kW continuous. The power would be transmitted to a smelter downstream where it is planned to produce some 210,000 tons of aluminium ingot per annum. The scheme would provide power for other parts of the country, inland navigation on the lake, and irrigation water for at least 200,000 acres of fertile land on the Accra Plains.

The Report on the Shire River Project, which has just been published by the Nyasaland Government, describes a most interesting multi-purpose scheme. It provides for control of Lake Nyasa and the Shire River by a seasonal bund on the river south of the lake, and a series of hydro-electric and flood control schemes lower down the river with a peak capacity of 360,000 kW. The control of the river would enable large areas of marsh land to be drained, and other promising areas to be irrigated. The reclaimed land could be used for the intensive cultivation of cash crops such as rice and the provision of power would encourage local industries. The scheme would open up a vast inland water transport system where transport is badly needed and it would do much to raise the standard of living and productivity.

Another good example of the engineer's contribution to conservation is the Snowy River Scheme in Australia. The Snowy River, rising on the eastern slopes of the Snowy Mountains, flows southward through country with an adequate rainfall for agriculture and wastes its great flow of water in the sea. On the western slopes of the Snowy Mountains there rise the streams that unite to form the Murray River which flows through hundreds of miles of arid plains before reaching the sea in South Australia. By building dams in the mountains great volumes of water will be impounded, one reservoir will store seven times the volume of water in Sydney Harbour, and then this water will be diverted by tunnels through the mountains to feed the Murray River system with 2 million acre-feet per year of irrigation water, which in its flow through seventeen power stations will give them a generating capacity of 3 million kW. The first power station is nearly finished and this great scheme when completed will provide Australia with two of her greatest needs for development, power and water, for she is one of the driest countries in the world.

It would be easy to multiply examples, just one more occurs to me that I have seen to show what the engineer can contribute in the remote districts of the world. The Warsak dam and power station on the Kabul River in the North-West Province of Pakistan, now under construction, will provide 60,000 kW of power and will irrigate 60,000 acres adjoining the arid mountainous country of the Khyber Pass. It will offer a new kind of existence to those wild frontier tribes, the Afridis and Mohmands.

Silt

There is another side to the picture. With the speed with which man is now changing his own environment he is apt to forget that the slow evolution of nature herself is still proceeding. The forces that smoothed the profile of our planet and produced the soil from rocks are still in action. Thousands of millions of tons of rock particles and eroded soils pass down the rivers each year, especially in flood seasons, as the carrying capacity of moving water varies with the sixth power of its velocity. That is the main anxiety of the dam builder for its future and he is faced with the dilemma that the more he uses a reservoir for flood control the shorter will be its life. In 200 years the great Lake Mead above the Hoover Dam will be an alluvial plain, and the lives of many reservoirs can be reckoned at a century or less. The Aswan Dam stands out for special reasons as almost unchanging.

Here the engineer becomes an agronomist as forestation, ground cover, and terracing can go far to prevent soil erosion and muddy streams. Subsidiary silt catchments can be built upstream but their life is limited. The problem of the deposit of silt in the reservoirs when the stream velocity is diminished is being studied and the persistence of a stream of denser water loaded with mineral particles along the bottom of the reservoir raised hopes that by opening sluices at the bottom of the dam in flood time the deposit will be reduced, but their scouring action is very local. Silt is the great problem of the future for the hydraulic engineer, as with the loss of storage capacity the output of the power station will become more and more dependent on the seasonal flow and more serious still will be the loss of perennial irrigation where it is dependent on storage. The ultimate solution may be new high dams, but the best sites have already been chosen.

Improved techniques

Let me now turn for a moment to the improved techniques the engineer has evolved in methods of surveying, dam construction, and model studies which have helped so much in the quick development of these bold hydraulic projects.

Surveys

Their first requirement is an accurate survey and flying has revolutionized the methods of large scale surveying as by means of aerial photography, with stereoscopic cameras to trace the contour lines, the preliminary work of mapping new schemes can be done with great speed and accuracy of detail. The nature of the rock and soil, soil erosion, forest cover and changes in the flow of rivers can be surveyed over wide areas with a completeness that was formerly impossible. For instance, 30,000 sq. miles of country were mapped in connexion with the Kariba and Kafue hydro-electric schemes on the Zambesi and 16,000 sq. miles for the Volta River scheme in the Gold Coast.

Again in these great schemes an accurate knowledge of the form of the underlying strata is an essential preliminary to engineering design. Modern geophysical methods enable this to be determined with great savings of time and effort. The measurement of the time taken by seismic waves, set up by an explosion, to travel directly or after refraction through the underlying rock enables the depth of the bedrock at various points to be determined with an accuracy of 10%. This method was used in the survey of the 300-yd-wide rocky gorge of the Kabul River for the Warsak scheme and it saved a large amount of difficult drilling.

The electrical resistance of soil and sub-soil depends largely on its moisture content and it varies from rock to rock, so resistance measurements between different points are another means of determining underground conditions and the existence and depth of a water-table. This method was used in the survey of the dam site in the Kariba Gorge on the Zambesi.

These are two examples of the progress that is being made in the application of geophysical methods in engineering which together with the new science of soil mechanics have contributed so much to the rapid design of these large multi-purpose water schemes.

Dam design and construction

The progress of concrete design and construction replacing the masonry dams of earlier times has given us the simplicity and grace of the great structures which are adding so quickly to the number of vast reservoirs in the world. This advance has come partly from the scientific analysis of the stresses in the structure, partly from the experience gained in methods of rapid construction by the diversion of water and boring of great rock tunnels, partly from the progress in our knowledge of the properties of concrete and partly from the improved mechanical methods of making and placement of the concrete which in the Grand Coulee Dam reached 20,000 tons of concrete a day. Then there are the methods of diminishing the heat rise during setting by the use of low-heat cements and the admixture of pulverized fuel ash, a pozzolanic material, and the removal of the heat developed by refrigeration or circulating water and also the " case hardening " of the outer surface of the concrete on the spillway sectors by vacuum application to remove air bubbles and water. The organization of these projects, the selection and transport of materials, the co-operation of civil, mechanical, and electrical engineers constitute a combined operation of great magnitude, and its success in so many parts of the world is a triumph for the engineer.

Hydraulic models

These great engineering works involve an interference with nature and experience has taught us that whenever we interfere with nature we must watch her reactions very closely with all the help that science can give. In no field is this more important than in interference with the flow of water. Changes of conditions brought about by new engineering works in a river channel, in a harbour or in coast defences may produce most unexpected results, and the number of independent variables involved is usually too great for a theoretical prediction. Luckily the technique of using scale models in which the effects of changed conditions can be speeded up a thousandfold is now sufficiently advanced to enable a fairly accurate forecast to be made if the model is well planned and its limitations clearly recognized. No model can reproduce in detail all the conditions of the original, for instance the size of the bed material in moving bed models cannot be scaled down to correspond with the other dimensions, and corrections have to be made when the similitude is imperfect. There is thus a limit to what can be expected of a model and great experience is needed in its use. However, the justification of the use of models has been established in many cases by a comparison of their results with those found subsequently when the work has been carried out. The model enables a comparison to be made of various engineering solutions of a problem and thus enables the most economical design to be adopted. The cost of the model is a very small fraction of the total sum involved.

Theoretical studies are also of importance for future developments for instance Hawthorne's analysis of the secondary flow around struts. Experiments in a hydraulic channel showed that the scouring of the beds of rivers near obstacles may be attributed to secondary flow and that the scouring is less marked with a bicuspid than with an elliptical profile.

The first experiments with loose boundary models were carried out by Osborne Reynolds in 1885 in connexion with proposals for improving the approaches of the Mersey. He showed that such models, even if they were very small, with a horizontal scale of 1 : 10,600 and a vertical scale of 1 : 396, roughly reproduced what was happening in the estuary. Later his techniques were developed by Gibson for river and estuary flow and drift.

Subsequently, many model laboratories were established on the continent especially in Germany, and from 1929 the Vicksburg experimental station and several other stations were started in the United States. The Delft Station dates from 1933, and Grenoble came into the model field in 1940. In 1919 experiments carried out at Poona by Claude Inglis with loose boundary models of various sizes showed that the changes which occur in nature can only be reproduced in very large scale models, and since then large numbers of such models have been constructed in India, and now, at long last, we have our own Hydraulics Station at Wallingford. Model studies are now almost invariably a condition of the contract for major hydraulic works and consequently the provision of adequate facilities at the Wallingford Station is a matter of serious concern in the overseas contracts on which the trade balance of the United Kingdom is increasingly dependent. This does seem to me an issue that concerns all three Institutions.

Irrigation and its problems

The present land area in the world cultivated for food is about 1,620 million acres and of this 230 million acres are under irrigation, much of it perennial, and these acres are of special value as they grow more than one crop a year under semi-tropical conditions. It may be possible to double this irrigated area in places where water is the limiting factor in cultivation, as in India, for example, where only 6% of the river flow is used in this way. Spraying is a much more efficient use of water than surface distribution as it can be controlled and the right amount of water applied when it is most needed. Much progress has been made with spraying in Arizona where water is precious and where the cost of the equipment is outweighed by the increased crop yields.

But irrigation is another interference with nature and the engineer's task is not finished when he has provided the irrigation water, since it brings with it the danger of salinity and alkaline soils which is now threatening large areas in the Punjab. All irrigation water contains some salt, which is also present in the soil, and unless there is efficient natural or artificial drainage the salt will accumulate and the soils may become alkaline with the loss of soil structure. In Egypt, where there is perennial irrigation, drainage canals carry off the surplus water, and standing in a cotton field in the Delta I have seen salt crystals growing in the drainage canal 10 ft below the level of the crop, so small is the margin of safety. The salt water from the drainage canals is finally lifted into the Mediterranean. In the Punjab, 500 miles from the sea, conditions are much more difficult. More water, either from canals or tube wells, is needed to leach the salt from the soil but some system of drainage and disposal of the drainage water on derelict land seems inevitable and represents a problem for the engineer. The same difficulty arose in the irrigated lands of Arizona and was solved by drainage schemes, and it will recur wherever irrigation is installed without precautions.

The Yangtse river in China provides, I am told, an example of a special type of irrigation which has been in existence for 2,000 years. Water is drawn off at favourable points into irrigation canals and distributed to the land and the drainage water is returned to the river, in which the volume of flow is sufficient to render the added salinity innocuous. The advantage of this method, when the lie of the land permits it and the steady flow of water in the main stream is sufficiently great, is its permanence. It illustrates too the important principle of not attempting to use irrigation water for a larger area than all the attendant circumstances justify.

Irrigation remains a complex problem. Pumping from tube-wells under suitable underground water conditions may help to solve it, but before reliance can be placed on this a survey of the underground water resources and their quality is essential, and a careful watch must be kept to see that they are not depleted. There is too a risk of changing quality as in certain parts of the United Provinces when after 6 years the water from the wells became brackish and useless. Water is so precious that this method should be regarded only as a second line of defence where it is possible to impound water from the maximum flow of rivers, as for example the Indus by engineering works in the Himalayas that would provide both perennial irrigation for great areas, power supplies and diminish the risk of floods and soil erosion.

We need to know much more about the movement of water in the soil, much more about the underground water resources and much more about the possibilities of these multi-purpose water schemes which utilize the world's limited supply of fresh water to the best advantage.

The future of water supplies

So far I have dealt mainly with water in relation to agriculture and there is the wider question of our ability to supply the rapidly increasing consumption of water in the cities and by industry. In some places wate is becoming the limiting factor to development and in Britain it is already difficult to locate a new industry needing much clean water or to fin inland sites with cooling water for power stations and industry. Nuclea power stations will almost certainly be sited on the coast for this reason The amounts required by modern industry are large—1,000,000 gal to make a ton of viscose yarn, and 400,000 gal a ton of steel. Here the engineer can help by the efficient treatment of effluents and sewage, by the reuse of water by means of cooling towers, or by returning well wate used for cooling to the strata from which it was drawn. Even in Britai water is needed for irrigation south of a line from the Severn to the Humbe if maximum crop yields are to be maintained. And I must not forget t mention the engineer's contribution to the conservation of human lif and the prevention of disease by sanitation and the provision of pur water.

In the United States the threat of water shortages has directed muc attention recently to the problem. The Conservation Foundation ha directed its main efforts into this field, and five major studies * hav recently been published dealing with various aspects. Statistics show tha 72% of the precipitation in the United States is returned to the atmospher by evaporation or transpiration through plant leaves, leaving 28% t reach the sea by rivers. Some 25% of the water demand is drawn fro underground reservoirs, and in many places the water-table is falling s that both on the eastern and western seaboard salt water is seeping i from the sea and damaging vegetation. One study on the conservatio of ground-water shows the need for much closer knowledge of the underground reservoirs and the movement of ground-water to replenish them in order to regulate their use.

Although the overall resources in the United States are sufficient it i clear that their effective utilization will be a serious factor in futur planning, to which surveys of climate and water flow are an essentia preliminary.

Another study examines the prospect of getting water from the se by various means, freezing, distillation, and electrolysis and the prospect seem to be most favourable for the purification of water by electrolysi

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* H. E. Thomas, "The conservation of ground water." McGraw-Hill, New York 951.

"Water in Industry." The Conservation Foundation and the National Association of Manufacturers, Dec. 1950.

E. A. Colman, "Vegetation and watershed management." Ronald Press, New York, 1953.

C. B. Ellis, "Fresh water from the ocean, for cities, industry, and irrigation." Ronald Press, New York, 1954.

L. B. Leopold and Thomas Maddock, "The flood control controversy: big dams little dams and land management." Ronald Press, New York, 1954.

between ion-exchange membranes. In large units the cost may be reduced to 2*s*. per 1,000 gal provided that a large sum is spent on development.

The effort devoted to these studies shows the urgency of the problem and water conservation is one of the most serious problems for the engineer in other countries besides the United States.

Land conservation and reclamation

I have already touched on the conservation of soil by measures to prevent erosion, flooding and salinity, now I come to the wider problems of land conservation and reclamation. In some places nature is encroaching on the land by coastal erosion, in others she is adding to the land areas by depositing silt at the mouths of rivers. These two effects are said largely to balance one another, but it is the engineer's task to prevent the one and take advantage of the other so as to increase the land area. Coastal erosion is slow but continuous, protection against it is difficult and costly and consequently it is undertaken mainly to protect industrial and residential sites or to guard against the danger of the flooding of large areas of agricultural land by high tides and surges. Jean Ingelow's poem " The High Tide on the Coast of Lincolnshire " gives a vivid picture of what has occurred in the past of which we had a sharp reminder in the disaster of 1953.

Holland more than any country is at the mercy of the sea as 40% of the land is below sea level, and there the techniques of protection by sea walls and sand dunes have been the subject of constant research and study. There again soil mechanics is most helpful and the study of the most effective plant and tree cover is providing the most economical solution. This was dealt with in such detail in the proceedings of your Conference on " Biology and Civil Engineering " in 1948 that I need only mention here, the contribution which these studies are making to land conservation. It is one of the important partnerships of man and nature.

In coastal protection model work again is indispensable in showing the effects, sometimes most unexpected, produced by sea walls or groynes so that they can be designed effectively and with economy. The force of water is so strong and its effects so disastrous that the protection of land against floods from sea and river must always remain a major task of the engineer.

At the mouth of some great rivers like the Ganges and the Nile nature through the ages has built up large areas of fertile land in their deltas without the aid of man. But in countries like Britain and Holland where land is precious man cannot wait and must help with reclamation.

In Britain the great reclamation of the southern fens by the " Adventurers " in the 17th century by drainage added 600,000 acres of the most productive land in the country mostly below high water level so that its existence depends on the maintenance of sea walls, river banks, and drainage. Since then some 75,000 acres of the Wash have been reclaimed when and where there was a silt deposit covering the sand which justified the cost of a new sea wall and drainage.

The history of Holland is a long fight against a slowly rising sea level to preserve the land by sea and river dykes. The Zuider Zee was lost to the sea as late as the Middle Ages, since when there has been a gradual regain of land by reclamation. Inland lakes have been drained and cultivated and in 1927 the great Zuider Zee project was started and with the closing of the 20-mile dam across its northern entrance it ceased to be a sea and became a freshwater lake, the Isselmeer, in the middle of Holland, which can supply water to the surrounding districts in prolonged periods of dry weather. This is being followed by enclosing or impoldering five successive areas with dykes behind the dam which will add over half a million acres to the cultivated area of Holland when the water has been pumped from them. The gradual accumulation of silt in these areas is being accelerated by the hybrid grass Spartina townsendii imported from England. This grass was first noticed by Lord Balfour of Burleigh in 1899 in Poole Harbour. He brought it to the notice of Francis Oliver who soon realized its potentialities for artificial reclamation as it will grow in brackish water and by slowing down the currents hastens the deposition of silt and its subsequent consolidation.

The policy of the Dutch has always been to shorten their coast line and so diminish the risk of floods, and after the disaster of 1953 they are embarking on the "Delta Project" of building dams across the tideway entrances to the great rivers in the south which when complete will halve the coast line that has to be protected.

Another country in which the richest soil is below sea level and must be protected by sea walls and pumping is British Guiana, where the original development made by the Dutch has been maintained by British engineers.

The Imperial Valley in California may before long present a special problem of land conservation. Thanks to irrigation the valley, which was once a desert, is now most fertile, growing three to four crops a year. The whole of it is below sea level and it owes its protection against the Pacific Ocean to the natural barrier which had been created by the deposits from the Colorado River in former ages. Each year coast erosion removes a large amount of the barrier, but until recently the barrier has been maintained by the silt of the Colorado which balanced the erosion of the sea. Now that the silt is being deposited in Lake Mead the barrier is being gradually reduced. In 1940, only 5 years after the construction of the Boulder Dam, the Gulf of California had advanced by 25 km. This is another case of man's interference with nature, and the problem is made more difficult by the fact that the erosion is taking place, not in the United States, but on Mexican territory.

And next there comes the cultivation of the land, when conservation means the raising of crops without the loss of soil fertility. It is only too easy to raise crops at the cost of fertility. And here since mechanization has invaded agriculture the task of soil conservation falls largely to the agricultural engineer. Britain has now the most highly mechanized farming in the world, and thanks to this the annual productivity is £660 per man employed, which is higher than the average productivity of manufacturing industry, £600.

Every type of soil and climate presents a special problem and it is for the engineer to provide the implements and methods which will optimize the yields of crops while maintaining the fertility of the soil. Water again is the limiting factor and I have already touched on the great economy and advantages of spray irrigation which we owe to the engineer. Its great advantage is that it can provide the right amount of water when it is needed. Penman has shown that the loss of water from the soil by transpiration depends mainly on solar radiation and in Britain this corresponds closely with the sun hours per month. The Meteorological Office now publishes monthly potential transpiration figures for the more important farming districts of the country to help farmers in deciding how much water is needed to make up for deficit in rain. So that with spray irrigation the use of water becomes more scientific and economical and the size of droplets can be regulated not to exceed 2 mm in diameter, as large drops break up the soil particles and consolidate them reducing the porosity of the soil. The provision of economical drainage is another problem for the engineer.

We are learning gradually how to make the best use of nature's gifts and under what conditions land is best devoted to forestry, grass cover, or arable crops. In all this engineering and soil mechanics are vital factors and on the engineer's contribution to mechanization and conservation will depend more and more the ability of the world to feed itself in the future years.

Energy

Next to soil and water I rank energy as the third great need of mankind since statistics show that the consumption of energy per capita determines the standard of living of a country. Here the engineer by the increasing use of water power is drawing on revenue and not on capital resources, though water power only provides 4 to 5% of the world's energy consumption. Other revenue resources are solar radiation, wind, tidal energy, geothermal heat, and the burning of timber and vegetable products. The last source provides some 18% of the total energy consumption today and there is not much prospect of any considerable contribution from the other revenue sources in the near future. Geothermal schemes in Italy and now in New Zealand are of local importance and the Bell Laboratory solar battery with a 10% efficiency of conversion of solar radiation energy to electricity points the way to important developments.

The main contribution of the engineer hitherto has been the steady rise in the efficiency of combustion appliances, of the generation of electricity, and of the gasification of coal. In the United Kingdom the increased demands for energy between 1920 and 1937 were met almost entirely by increased efficiency of energy conversion and utilization representing a saving of at least 47 million tons of coal. There is no need to stress the importance of a continued effort for higher efficiency but fortunately the possibilities of the nuclear power station have come just when there is little prospect of large additions to the output of coal. Here again is a combined operation for the electrical, chemical, mechanical and civil engineer which will add a hundredfold to the world's energy resources. Important as electricity is as a source of heat and power our economy is linked in many ways with liquid fuel, and the coming of nuclear power will enable the coal and oil resources to be used in the future more and more as a source of chemicals and of the liquid fuels on which for many purposes our economy is based.

We shall watch with envious eyes the great SASOL plant in South Africa just coming into operation to make petrol and other products from the cheapest coal in the world costing 3*s* 6*d* per ton.

Raw materials

I come last to the engineer's contribution to the conservation of raw materials by added efficiency in their extraction, processing and use. It is a long story which might easily become a wearisome catalogue so let me select a few of the outstanding examples and particularly those of special significance for the future.

Extractive metallurgy

We are living in a metal civilization and in spite of the progress that is being made in the use of plastics and bonded materials as alternatives we must look to an increasing use of metals in the future. For many engineering purposes they are indispensable, and progress in metallurgy is often the limiting factor in engineering design. All recent surveys of resources like the Paley Report make it clear that we shall become increasingly dependent on lower grade ores, often containing several finely intergrown minerals which must be separated. For the treatment of such ores the older physical methods of ore dressing producing concentrates for smelting are proving inadequate and they are now being supplemented by various chemical engineering techniques. There are two main developments, in one the metals are leached out by various solvents sometimes under pressure, and are then separated by different methods precipitation, electrolysis, or ion exchange as in the case of uranium. For example a large ore deposit containing less than 1% of copper oxide is being leached with sulphuric acid. Bacterial oxidation of a low grade partly oxidized, copper sulphide deposit is being tried with the same object. Nickel sulphide concentrates are being leached with aqueous ammonia and oxygen under pressure.

The other method consists in treating ores in fluidized beds at controlled temperatures with various gases. Iron oxide can be converted to magnetite for magnetic extraction, and sulphides of copper, nickel, and cobalt can be roasted to sulphates for subsequent leaching with water. By temperature control an almost complete separation of copper from iron can be effected in this way.

The use of active carbon to extract metals from dilute solution has also considerable possibilities. For instance gold can be extracted continuously with economy in the amount of cyanide required, and a considerable saving in the number of thickeners and continuous drum filters which are needed when the gold is recovered by precipitation with zinc dust.

The United States Bureau of Mines is carrying out large scale experimental work on the chemical treatment of low-grade manganese ores by sulphating followed by leaching and precipitation. There are also possibilities of recovering manganese from open-hearth slag by fluidized bed roasting followed by extraction with ammonia and ammonium carbonate.

Another important aspect of the chemical approach in attacking ore treatment problems is the extraction of values from the slimes which are often unavoidable and may carry sufficient of the ore to prevent the economic exploitation of a low-grade deposit. Selective flocculants are giving promising results and polyvalent ions are being used as flocculants in the recovery of uranium from enormous quantities of slimes from the treatment of Florida phosphates.

These new methods are likely to extend greatly the range of the ores that can be treated profitably and thus increase the potential resources of metals in the world.

Hitherto most of the development work in this new field has been done in the United States and Canada where the exploitation of mineral wealth is a major part of the economy. The old distinction between the processes used in ore dressing and extractive metallurgy is disappearing with these chemical methods of ore treatment. In the future there must be a much closer link between the schools of mining and chemical engineering in this country if we are to keep abreast of the times.

The processing of raw materials and synthetics

There is no better example of the great advances that have been made in the scientific processing of raw materials than the improvement in the refining of crude oil over the past 30 years, and it was responsible for the introduction of the fluidized bed, one of the revolutionary advances in modern techniques. By the improved design of stills, by better control and heat recovery, the overall thermal efficiency has been raised by 25%, the amount of refinery fuel required being less than 2% of the crude oil distilled. Then the amount of motor gasoline produced today by thermal reforming, catalytic cracking, polymerization of olefines and other new techniques is on a world basis 36% by weight of the crude as compared with 18% by straight distillation 30 years ago, and the octane number of the gasoline is much higher with the resulting improvement in fuel economy.

Further there has been a great increase in the range of products and their quality to keep pace with technological progress, for instance in the development of aero-engines. Synthetic detergents, paint additives, cutting oils and an immense range of lubricants are among the most significant advances. Propane and butane are sold as "bottled gas" instead of being burnt as refinery fuel. A new aliphatic chemical industry has been based on refinery gases, and platforming adds largely to the supply of aromatic chemicals like benzene which are now in such great demand.

There are many other parallel examples of this trend of modern industry to make better use of its new materials—rubber, cellulose, leather and above all perhaps in importance, the scientific processing of food. This is now a great industry which contributes so much to the transport of food without deterioration and to its safe storage.

Synthetics in the 20th century have done much to change the pattern of our life and synthetic ammonia has relieved our anxiety about nitrogen fertilizers, which by increasing the output per acre are a most effective means of conservation. Plastics and synthetic fibres not only supply many new needs, but as substitutes for vegetable products they relieve the demand for them and thus leave more soil for food production. The output of rayon and viscose already exceeds that of wool.

But man's power to synthesize materials economically is limited to simple molecules and their polymers. There is no hope of his manufacturing the complex proteins and polysaccharides he needs for food without the aid of living organisms, which make them so accurately and cleanly by their templet methods. Fermentation is one of the oldest industries but it is only in this century that microbiology has revealed the almost unlimited possibilities of the living cell. From Pasteur and Koch the microbe got a bad name, but without it life on this planet could not exist. The microbe is a great conservationist and it deserves a better reputation. The amount of nitrogen supplied to the soil each year by fertilizers is only a small fraction of that fixed by living organisms in the soil.

Rahn in a comparative study of the criminology of the microbe and mankind in the United States concluded that only one micro-organism in 30,000 is a carrier of disease, while in the year of his census one inhabitant in 17,000 was convicted of murder. And as Professor Kluyver pointed out in his Leeuwenhoek Lecture the amount of microbial protoplasm in the world is probably twenty times as great as that of animal protoplasm, so there is no lack of ready helpers with an amazing adaptability. The harnessing of micro-organisms in the production line in friendly tasks is one of the great ventures of the near future—biochemical engineering.

Structures

Among the great economies in the use the engineer makes of materials I put structures high on the list. I remember seeing in 1901 the first skyscraper in New York, the old Flat Iron Building, soon to be dwarfed by the giants of that amazing skyline of Manhattan Island. The foundations of these great modern buildings are based on site studies using the techniques of the new science of soil mechanics. I have already touched on some of its new methods which are applied to big dams, and as Dr Lea dealt with them so thoroughly in his recent Unwin Lecture I need only refer you to this for the scientific methods that are now available to investigate the sub-soil characteristics and the various techniques for designing and constructing the foundations on which buildings can be erected with economy and security. As a matter of interest I got the costs of a number of these site studies and they averaged about 0·2% of the cost of the building, some being as low as 0·03%, showing the small addition these invaluable studies make to the total cost.

Then in the structures themselves, steel and reinforced concrete with prestressed and often precast units have made the main contributions to new designs and economies. Progress in the theory of structures based on the elastic limit of materials, in the quality of steel and in the fabrication of steel members, and especially long experience, have produced large savings in the amount of steel required and the cost of erection. I have a special interest here as one of the three steel-framed buildings which Dr Baker, as he then was, investigated for The Steel Structures Research Committee, was one in which I was responsible for the co-ordination of the architects and the engineers. That investigation illustrates a principle I should like to adumbrate. Every major engineering project should be treated as an opportunity for research with the necessary scientific measurements in order to correlate the predictions of design with the results obtained, and to point the lessons for conservation. We did that at Euston House.

The results of Professor Baker's investigations showed the limitations of the elastic theory for practical use owing partly to its complexity in large structures and partly to the discrepancies observed in the stresses in the framed structures due to the vagaries of riveted and bolted beam-to-structure connexions. In structures designed by the elastic theory, some deformation must occur at working loads due to stress concentrations and lack of fit during erection. Were it not for the ability of mild steel to undergo plastic deformation, such structures would prove unsatisfactory in service.

Professor Baker's development of the plastic theory of structures provides a basis for design in the calculation of ultimate strength and in so doing forces a realistic appreciation of the importance of ductility. One of the most important consequences of basing design on ultimate strength is that full use can then be made of the advantages of redundancy and of the rigid joint construction made possible by the modern development of welding. This leads on to the consideration of load factors instead of the old-fashioned factors of safety. Experience in the erection of single-storied buildings designed on the basis of the plastic theory shows economies of 15 to 30% as compared with similar buildings designed by orthodox elastic methods. The plastic method not only makes it possible to design buildings more economically but opens the way to the development of new steel structural forms.

The increasing use of concrete in structures has helped the conservation of resources in two ways. First by its use in conservation schemes like coastal protection, harbours, and dams. Secondly by the use of less valuable and more generally available raw materials in place of steel, with a consequential economy in coal.

A reinforced concrete structure requires on an average about 40% of the weight of steel compared with a normal steel structure and the use of prestressed concrete in flexional members requires about one-seventh of the steel. In some structures (e.g., multi-storey buildings) the extra concrete required is almost negligible but in others (e.g., bridges) the saving in steel has to be offset by an increase in the use of cement and aggregate. Even here, however, it may not be more than about 25% because the same amount of concrete is used for the foundations in both instances.

The economy of coal follows since 35 cwt of coal are needed to make a ton of steel and 8 cwt to make a ton of cement. To the latter must be added the coal equivalent of the energy required in providing the average amount of 4 tons of aggregate which must be added to one ton of cement in making concrete. As a rough guess the replacement of a ton of steel by a ton of reinforced concrete saves about a ton of coal.

The working and fabrication of metals

I turn now to the great economies in material and effort that have resulted from the scientific development of the methods of working and fabricating metals and testing the quality of the product. The improved methods of welding, casting, pressing, extrusion, oxygen cutting, and machining have revolutionized metal fabrication, and the use of X-rays, gamma-rays, ultrasonics and other devices have enabled the products to be tested with much greater certainty. This is a steel age and the efficiency of the modern steel works and the continuous strip mill is a great contribution to our economy.

Welding has had the most widespread effect in the ubiquity of its applications both to fabrication and repair. With the mechanization of farming, just think of the value of an electric welder in repairing quickly a defect in a harvester in the critical days of gathering crops, and the other applications of welding to repair are manifold. The various forms of electric welding, D.C., A.C., oxy-acetylene, argon arc, nitrogen arc, spot welding, and butt welding have made it applicable to almost every metal, have saved immense amounts of material and have simplified construction by eliminating the need for rivets, gussets, and overlap. In steel-framed buildings there are economies in materials up to 25% and the absence of rivet holes means that design can be based on the full sectional area of tension members. Welding is essential for the use of plastic design methods which requires that all joints must be completely rigid. In bridges welding may show a saving of 25% over a riveted design and a transfer of many tons to the permissible live load. In ships there may be economies up to 17% of weight for an 18,000 ton tanker, with the advantage of the smooth contour of the welded hull and a corresponding saving in fuel consumption. The substitution of welding for the forging of pressure vessels has not only cheapened production but has made possible many improved designs.

Next to welding, improved precision methods of casting have contributed to great economies : centrifugal casting, die casting, shell moulding, and the elegant lost wax investment method for small castings. In the latter a pattern is made by injecting wax into a die, the wax is then coated with a fine refractory and bonding agent and invested with a slurry of refractory which sets to form a mould. The wax is then melted out, the mould is fired and used for pressure casting. By this means intricate precision castings can be made with a fine finish with a great reduction in the machining required and an average saving of material of 50%. Gas-turbine and jet-engine compressor blades with their complex aerofoil sections and shapes can be made in this way much more cheaply than by machining them out of solid bars. The centrifugal casting of pipes gives a more uniform thickness of sounder metal and a high yield. Bearing metal liners can be cast in by this means requiring little or no final machining.

Improvements in machine tools have led to savings of labour rather than direct savings of material, to greater accuracy and to finer surface finish. Higher cutting speeds, to take advantage of carbide-tipped tools, and also greater flexibility of speed have been obtained by direct electrical drive with higher powered motors. Higher speeds and improved quality of the products have also been helped by research into the form of the cutting edge of the tool and by the provision by the metallurgist of new alloys better suited both to machining and to the work they have to do. While there has been much progress in automatic machines, the inclusion of the copying principle on standard machines has given them greater versatility and allows of repetition production at high speeds for large or small batches, when the use of a fully automatic machine would not be economical. Improvements in casting and drop forging enable work to be transferred directly to precision finishing machines with a high degree of accuracy.

The latest development is the automatic machine with electronic control and a computor which can read a drawing and translate it directly into work, pointing to the automatic factory of the future.

Wear and corrosion

One of the major fields in the conservation of metals is in the application of research to the problems of wear and corrosion. Bowden in his Hawksley Lecture showed how the contact of two metal surfaces invariably results in a transfer of particles of one metal to the other and described the conditions under which various types of lubricants can minimize this transfer and loss of material. The action of the lubricant in diminishing friction results in a saving of energy, friction in a motor car absorbs 20% of the motive power, but the major contribution of lubrication is in the saving of wear and in prolonging the life of the moving parts. The possibility of higher speeds and higher bearing temperatures has been made possible by the discovery of lubricants which are stable over a higher range of temperatures like the silicones and polyfluorethylene and the use of bearings made of sintered metals like copper which can carry the liquid lubricant. Similarly improvements in cutting liquids to remove the heat generated by the plastic deformation of metal by the machine tool and diminish friction have helped in the high speeds, in the life of the tool, and in the quality of the machined surface.

Astronomical estimates have been made of the loss of metals, particularly iron and steel, by corrosion. With the increasing amounts of metal going into service and the growing use of thinner sections, for instance in the steel pipelines that are carrying oil and natural gas many thousands of miles, protection against corrosion becomes increasingly important to guarantee the long life of these costly installations. Much progress has been made in methods of pre-treatment, in the application of protective coatings and wrappings, but the possibility always exists in a long pipeline of weak spots where corrosion may begin. Here, as with steel structures under water and with ships, the use of cathodic protection on an engineering scale either by sacrificial anodes or by an impressed electromotive force is adding greatly to the life of these structures and avoiding very costly failures and replacements. Cathodic protection was invented by Humphry Davy in 1825 but it is only now coming into general use on an engineering scale. He applied it to the protection of the copper hulls of warships, but the Admiralty discarded it as it encouraged the growth of barnacles. It is sad to remember that Davy left England under the strain of the disappointment and public criticism and died abroad, seeking the consolation of a philosopher in travel. Today his invention is a major factor in conserving engineering structures.

The conservation of human labour

I have left to the last the engineer's conservation of human effort, both manual and mental, by mechanization, automatic control and electronic computors. In the race for productivity mechanization is the pace maker. Recent figures from the United States show that the productivity per head has doubled with the doubling of the horse-power employed. And now a new factor is coming in, as automatic control not only replaces man-power and accelerates production but its products are of higher quality. Electronic devices are much quicker and more accurate than the human brain and can be used for an infinite variety of control purposes. And whereas the human senses can only deal with one operation at a time, an electronic system can regulate simultaneously the many interlocking controls required in a large plant. The nation-wide automatic dialling system of telephones in the United States is a good example. Then analogue computors can simulate complex operating problems and provide a short cut to the answer, digital computors can solve in a few minutes differential equations which would otherwise require a prohibitive number of man-hours of work.

There is no need to dwell on the contribution of mechanization to the economies of the production line. Automatic control is another story. On the one hand great progress has been made in the mathematical theory of control design which is directly applicable to the design of control equipment for systems in which the dynamic characteristics of the mechanisms are known. On the other hand progress in instrumentation and in the technique of servo-mechanisms has led to the widespread application of automatic control to machines and continuous processes which were not originally designed with this in view. If the maximum advantage is to be made of this new approach, its philosophy and theory must start in the design phase and be applied continuously. This entails both an appreciation by the designer of its possibilities and the co-operation with him at each stage of the control engineer who has specialized in control theory and instrumentation. A big educational problem is involved which is vital to the industrial future of this country, especially now that full employment has been reached.

Information from the United States and the Soviet Union is strong evidence of the much greater awareness of the urgency of this problem in both those countries. In the United States there are said to be close on 2,500 companies in the control business employing 8,000 graduate engineers who have specialized in this field, and there are 15,000 more in the user industries. Russia has concentrated her mathematical ability on the theory of automatic control and her numerous applications of it in industry show how effectively she has grasped its philosophy. She was operating in 1951 the first complete automatic production line of an aluminium alloy piston from the ingot to the finished product fully tested and examined, and she had automatic plants making cylinder blocks in 1948 and also agricultural machinery. Her automatic tests of surface finish are most effective and ingenious. Evidently her objective is high quality machine production using a minimum of skilled personnel, thereby increasing her competitive position with the other great industrial powers of the world. This is the Russian engineer's contribution to conservation.

I do not wish to end this review of the engineer's achievements on a gloomy note so far as Britain is concerned, but in spite of the interest shown by a few firms, I must draw attention to the urgent need for a more active and general recognition of the future importance of control engineering in this country.

Conclusion

And now what emerges from this patchwork survey of the engineer's massive contribution to conservation, the need for which will increase with the growing population of the world and the depletion of its capital reserves ? I said at the end of my James Forrest Lecture over 20 years ago, " Progress today demands intense specialization on the one hand and on the other the widest outlook and knowledge of what is happening in other fields—intensive research and extensive application." And this is even truer now with the new techniques that have developed so rapidly since then. By and large, all are based on the application of research and their complexities breed new kinds of specialists with the dangers that involves. The remedy is a synthesis of specialists which indeed is the pattern of the combined operations which these great engineering projects inevitably demand. This, I am sure, was the thought in Graham Clark's mind in seeking a better understanding between the Institutions and of the need for their co-operation in the future.

And this survey brings out another point, the need for an ever closer working with nature. You cannot control nature. She will always have her way but with the more intimate understanding we are gaining of her ways a new partnership is possible with the great forces and resources that she embraces.

One final lesson emerges. In each generation there is a limit to what is possible, a limit imposed by the resources and skills that are available to mankind. In the future those resources and skills must be used to the best advantage, and with their unequal distribution among the countries of the world, some form of planning is ultimately inevitable, based on surveys of world needs and world resources. Only in that way can they be conserved for the use and convenience of man.

The Chairman, moving a vote of thanks to Sir Harold Hartley, said that the lecture had been enjoyed by all present. He himself had found it fascinating, and he wished to thank Sir Harold not only for the vast amount of information he had given, but for the very agreeable and pleasant way in which it had been presented. The three Institutions had every reason to congratulate themselves on the choice of their first Graham Clark Lecturer. He had great pleasure in proposing that a hearty vote of thanks be accorded to Sir Harold Hartley.

Mr J. Eccles, President of the Institution of Electrical Engineers, who seconded the vote of thanks, said that the Graham Clark Lecture, of which this was the inaugural lecture, had been given to commemorate a great man who had served the Institution of Civil Engineers well and who, in his capacity as Secretary, had probably done more for young engineers and for their welfare and education than perhaps anyone else individually in the Institution. Graham Clark's thought for the widening of the outlook of the engineer and particularly to lift his sights from pure technology to something more appropriate to his existence as a human being, had been the theme on which the three Institutions had dwelt in arranging for these memorial lectures.

He knew of no one who could have been more appropriately chosen to deliver the first lecture than Sir Harold Hartley. The vindication of that was in the scope and range of the lecture which Sir Harold had given. Sir Harold had covered a vast territory both geographically and technically, and had shown that the contribution of the engineer to the service of mankind was truly magnificent.

Some day there would be other lecturers who would tell the story of what had happened and what mankind had done with all those benefits which the engineer had conferred—why, for example, with all the horsepower in the world, it was quicker to walk from the City to Trafalgar Square than to ride in a mechanized vehicle! The way in which those resources had been used for the benefit of mankind was extremely important. Beyond and above all that was the place and purpose of the engineer's achievement in the spiritual and moral welfare of mankind.

Those were things that had got to be thought through and were being thought through by individuals and groups, and they would no doubt form the basis and the substance of future Graham Clark Lectures.

A good start had been made, and he expressed, on behalf of all those present, grateful thanks to Sir Harold Hartley for giving such a comprehensive lecture.

The vote of thanks was put to the meeting and passed with acclamation.

CORRESPONDENCE
on a Paper published in Proceedings, Part I, January 1955

Paper No. 5998

"The Computation of Shrinkage and Thermal Stresses in Massive Structures"†

by

Olgierd Cecil Zienkiewicz, Ph.D., B.Sc.(Eng.), A.M.I.C.E.

Correspondence

Mr T. K. Chaplin (Scientific Officer, Soil Mechanics Division, Building Research Station, Watford) observed that the values of θ used in Fig. 4a gav very irregular values of $\nabla^2\theta$, probably as a result of their being interpolate from the drawn isotherms of Carslaw and Jaeger.[6]

Since $\nabla^2\theta$ controlled equation (3), namely, $\nabla^4\psi+\nabla^2\theta=0$, Mr Chapli would have expected the irregularities in $\nabla^2\theta$ (plotted in Fig. 9) to hav produced some approximately corresponding irregularities in the stresse $\delta^2\psi/\delta y^2$ in Fig. 4c, but they scarcely appeared.

To show the effect of using a very coarse mesh he had calculated th stresses given by a mesh length double that used in Fig. 4b. Although i that mesh there were only three independent values of ψ, surprisingly goo values were obtained for the stresses in the central region (Fig. 10), and a the outer boundary the difference was about a quarter of that given by the finest mesh. The trend of the successive stress values at the oute boundary suggested that even the Author's finest mesh might be under estimating the maximum stress by as much as 10%.

In Fig. 4a there appeared to be errors in the printed θ-values of 0·51 and 0·703, which he thought should be 0·570 and 0·730.

The Author, in reply, thanked Mr Chaplin for his detailed contributio to the Paper and the labour he had put into the extension and checking o some calculations. The error which had been pointed out in Fig. 4a ha occurred during tracing and the correct values, as given by Mr Chaplin had in fact been used in the computations.

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† Proc. Instn Civ. Engrs, Pt I, vol. 4, p. 88 (Jan. 1955).

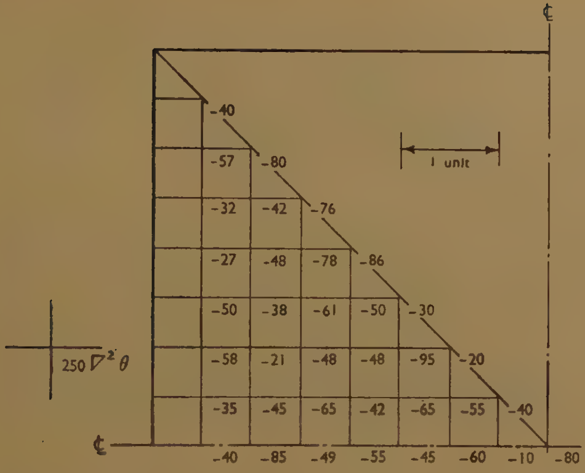

FIG. 9.—VALUES OF $250\nabla^2\theta$ DURING COOLING OF A SQUARE PRISM

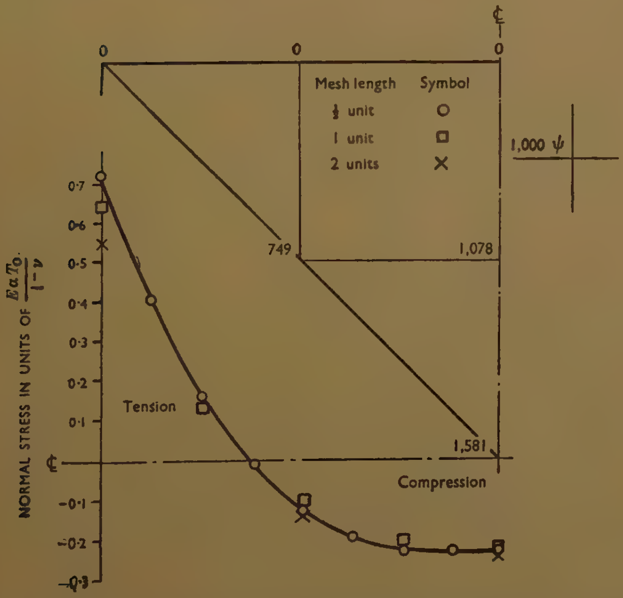

FIG. 10.—SOLUTION FOR A VERY COARSE MESH (UPPER LINE) AND STRESSES GIVEN BY VARIOUS MESH SIZES (LOWER LINE)

As Mr Chaplin had rightly remarked, the values of temperatures take in Fig. 4 were only approximate—the problem having been introduce mainly to illustrate the general methods of solution. The reasonabl smooth distribution of stresses resulting from rather irregular values $\nabla^2\theta$ was even more striking in the other examples, where isolated values that residual on a particular line gave smooth and continuous stre distributions at least on one side of such a line.

There was no method known to the Author by which the degree approximation reach could be estimated with mathematical precisio Comparison with problems for which known analytical solutions existe served often as a useful guide to the accuracy attainable and in specifi cases the advance to finer meshes gave an indication of the rapidity convergence. In the example of Fig. 4 it did indeed appear that th approximation to the boundary stresses might be of the order of 10 with a much closer estimate within the interior of the prism.

CORRESPONDENCE
on Paper published in Proceedings, Part I, May 1955

Paper No. 6051

" New Northam Bridge, Southampton "†

by

Frank Leslie Wooldridge, M.I.C.E., John Cuerel, B.Sc., M.I.C.E., and Knud Rosenauer Hauch, O.B.E., B.Sc.

Correspondence

Dr K. Hajnal-Kónyi was particularly interested in the test of a 105-ft beam described on pp. 284–6. In his introductory remarks Mr Cuerel had pointed out that there was no " explosion " of the concrete at failure.

However, the maximum load was reached when the deflexion/span ratio was only 1/210 and the time interval between that stage and final failure was only 10 min. A deflexion of that order did not give sufficient warning and even if the dangerous condition of the beam was detected, it would be obviously impossible to prevent failure. On the contrary, any attempt to interfere might result in a fatal accident. From the point of view of safety there was hardly any difference between failure by " explosion " and failure as described in the Paper.

A distinction had to be made between limiting load at which a certain limiting condition such as excessive deflexion or cracking occurred, and failing load. In the test beam those two loads were identical. That should be avoided in a structure wherever possible and there should be a reasonable margin between the two loads.

A beam when overloaded beyond a certain limit should appear to be dangerous, although, in fact, it was still safe, whilst the test beam appeared to be safe when its failure was imminent.

The foregoing remarks did not, of course, apply to the beam as it was used in the completed structure, since by the addition of in-situ concrete it was transformed into an " under-reinforced " beam.

Had a beam of that type been tested, the mode of failure would have been quite different, and a deflexion much greater than 6 in. would have been reached at a load below the maximum.

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† Proc. Instn Civ. Engrs, Part I, vol. 4, p. 269 (May 1955).

Dr Hajnal-Kónyi wished to emphasize the undesirability of "over-reinforced" beams. In ordinary reinforced concrete their application was prohibited by the Code and the other extreme was reached by providing much more compression steel than necessary. There was no justification either for the use of "over-reinforced" beams in prestressed concrete since the mode of failure should be the over-riding consideration of design. Dr Hajnal-Kónyi attached far more importance to a wide margin between limiting and failing load than to an excessive load factor without any margin between those two loads. Whilst an "under-reinforced" well-bonded prestressed concrete beam far below the range of the limiting percentage for "over-reinforced" beams was perhaps the best form of construction obtainable to-day from the point of view of safety, an "over-reinforced" prestressed beam was the worst, and comparable with cast iron.

Mr A. W. Shilston stated that his remarks were confined to questions of detail. He was very interested in the original scheme, presented to the tendering contractors, of forming the pier bases. Having some knowledge of tidal conditions in the area of the works site he assumed that the engineers had in mind driving the piles from a temporary piled staging. In that connexion he would like to ask to what order of accuracy the external raking piles were expected to be driven so as not to impair unduly the line of the pier faces. It might have been felt, of course, that since the piers came under close inspection largely only from river craft, no very great accuracy was called for, and that small undulations on the pier faces were permissible.

Regarding the driving of the 10-in. × 10-in. prestressed concrete piles to support the north and south abutments, Mr Shilston asked to what approximate level they had been driven and with what type of piling-hammer. Had jetting been employed, and did the Authors have any reservations regarding the use of prestressed piles in that particular instance?

To what level were the cofferdam piles driven, and was any difficulty experienced in extracting the piles, which had been used as a back shutter against which to cast the pier bases?

Since the chemical consolidation around the piers would be carried out after the cofferdam piles had been pulled, were any tests made to prove the extent to which the cementation was effective?

Mr Shilston asked if amplification could be given to the concreting procedure. The river piers were apparently cast in 3-ft lifts. Were they placed for the full length of the piers without stop ends? What formwork stripping periods were allowed, and what special surface treatment to the concrete, if any, was specified? He also noted that a pan-type mixer was used in the casting of the precast units. Did the engineers consider it desirable to specify the use of that type of mixer for prestressed work in general? Could some indication also be given of the frequency of the cube crushing tests?

Mr Shilston had always been slightly reserved about the extensive use of prestressed concrete in Britain owing to the not very high class of labour attracted to the civil engineering industry at the present time. Did the contractor have any difficulty in getting and training the right type of men to observe the unusually high standards of workmanship that had obviously been called for?

In conclusion, no reference had been made to the Royal Fine Arts Commission. Had that body been asked to express its views on the aesthetics of the proposed design?

Mr Wooldridge, in reply to Mr Shilston, observed that judging from the high quality of workmanship achieved in the early stages of the job and the high rate of production ultimately reached in the beam casting yard, it would seem that the man on the job had not been slow in becoming proficient at producing an article conforming with the specification required. Both the design finally adopted as well as the earlier proposals had been submitted to and fully discussed with the Royal Fine Arts Commission.

Mr Cuerel, in reply, said that in his introductory remarks he had drawn the attention of the framers of regulations to the behaviour of the test beam. According to the rules they proposed, which he considered unsound in principle, the beam was definitely "over-reinforced." Its unexpected behaviour in the manner reserved for the superior class—the "under-reinforced"—seemed even more astonishing when it was considered that the beam, in the form tested, had been similar to those used in the experiments leading to the formulation of the rules, in being loaded under conditions far remote from those obtaining in any practical structural element after incorporation in the work.

Dr Hajnal-Kónyi appeared to be disappointed in that there was no "explosion" on failure of the test beam, and he had taken great liberties with the facts in an attempt to prove that there had been an "equivalent explosion." Clear signs had been apparent to all those who had witnessed the test that the loading was excessive long before the ultimate had been reached; it was untrue to say that the distress load and the failing load were identical; and comparison with cast iron was absurd. Dr Hajnal-Kónyi was right in emphasizing the undesirability of too much wire, but his reason, taken in the light of the complex action of a practical structure, was merely secondary. Excessive steel was not economical.

With regard to Mr Shilston's question on the accuracy expected in the driving of the external piles in the original pier-base scheme, it had been anticipated that the errors in positioning would not be greater than would permit the heads of the piles to be pulled to a true line; that variations in rake would not amount to a " stagger " of more than an inch or so at low-water level; and that the resulting small undulations would be obscured by weed and slime.

Mr Hauch, in reply, remarked that the prestressed concrete piles in the south abutment had been driven to approximately − 30·00 ft O.D. and those in the north abutment to approximately − 25·00 ft O.D. All piles had been driven with a 4-ton single-acting steam-hammer.

The cofferdam sheet-piles had been driven to − 26·00 ft O.D. and had been extracted with a No. 20 Zenith extractor. The pulling of the first few piles in each cofferdam had been slow, but no great difficulty had been experienced, except in the very few cases where piles had been damaged during driving.

In order to test the quality of the soil consolidation, a 2-ft-dia. perforated steel barrel had been sunk to low-water level and filled with a gravel mixture of proportions closely resembling the natural strata. The barrel had been covered with excavated river material and injected with chemicals during high water. On later examination, the contents of the barrel had been found to be satisfactorily consolidated.

The 3-ft lifts in the river piers had been cast in one operation without the use of stop-ends, and the formwork had usually been struck after about 48 hours, subject to weather conditions. Owing to the use of internal vibrators and plywood shuttering, very little surface treatment had been required. Test cubes had been taken from each major pour and crushed, usually at 7, 28, and 84 days, and in the case of beams also at 3 days.

Mr Hauch did not understand Mr Shilton's remarks regarding the class of labour in the civil engineering industry. Surely, the quality of the work was, as in any other industry, largely in the hands of the supervisory staff, whether the contractor's or the client's. He had no doubt that the British civil engineering workman was fully capable of producing work to high standards, provided the importance of such standards was properly explained to him.

ELECTION OF ASSOCIATE MEMBERS

The Council at their meetings on the 21st June and the 19th July, 1955, in accordance with By-law 14, declared that the following had been duly elected as Associate Members :—

Adamson, Eric, M.Eng. (*Liverpool*).
Allison, Gordon Francis, Grad.I.C.E.
Anderson, Hedley Robert Muir, B.A. (*Cantab.*).
Anderson, Kenneth Morgan, B.Sc. (*St. Andrews*), Grad.I.C.E.
Armytage, Robert Geraint, B.Sc. (Eng.) (*London*).
Arrowsmith, Edmund Joseph, B.Sc. (*Durham*).
Ashwell, Derek George, Ph.D., M.A. (*Cantab.*).
Bailey, John William, B.Sc.Tech. (*Manchester*).
Bailie, Cyril George Archibald, B.Sc. (*Belfast*).
Baillie, John Alexander, Stud.I.C.E.
Banks, Peter Albert, B.Sc.(Eng.) (*London*).
Bannister, Geoffrey, B.Sc.Tech. (*Manchester*), Grad.I.C.E.
Barfod, Ove Tang, B.Sc. (*Copenhagen*).
Beach, Jack.
Beal, Stuart Manson, B.Sc.Tech. (*Manchester*).
Beattie, Lionel Silvester.
Bell, David Alston, B.Eng. (*Liverpool*).
Bennett, Richard Arthur Harlow.
Bentley, Henry George, B.Sc.Tech. (*Manchester*), Grad.I.C.E.
Berry, Richard Anthony Protheroe, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Best, Frederick Herbert.
Bond, Jack, B.Eng. (*Sheffield*).
Brady, Walter Neville, B.A., B.A.I. (*Dublin*).
Bramwell, John Edgar Dale, B.Sc. (*Witwatersrand*).
Bristow, Thomas Arthur George.
Brookes, Edward Michael, B.Sc. (*Durham*).
Brown, Brian Mercer, Stud.I.C.E.
Brown, Eric Hugh, Ph.D., B.Sc. (Eng.) (*London*).
Brown, Robert William, B.Sc. (*Bristol*), Grad.I.C.E.
Bushell, Charles Joseph, Grad.I.C.E.
Calder, William Buchanan, *O.B.E.*, B.Sc. (*Edinburgh*).
Carling, Peter George, B.Sc. (*Wales*).
Carlisle, John Frederick, B.Sc. (*Cape Town*).
Carpenter, Raymond Charles, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Chapman, Kenneth Geoffrey, B.Sc. (*Leeds*).
Chatterjee, Binoy Kumar, M.Sc. (Eng.) (*London*), Grad.I.C.E.
Clarke, John.
Clarke, Keith Brian, B.Sc.(Eng.) (*London*).
Clinton, Samuel, Grad.I.C.E.
Cooke, Peter Campbell, B.A. (*Cantab.*), Grad.I.C.E.
Coombes, Lewis Hamilton, B.Sc.(Eng.) (*London*).
Craig, Arthur John, B.Eng. (*Liverpool*), Grad.I.C.E.
Crann, Harry Howard, Ph.D., B.Sc. (*Birmingham*), Grad.I.C.E.
Crompton, Derrick, B.Sc.(Eng.) (*London*).
Crosby, John Charles, B.Sc.Tech. (*Manchester*).
Currie, David Stewart, Grad.I.C.E.
Curtis, Ronald Cyril, *M.B.E.*
Dehn, John Patrick, B.Sc. (*Manchester*).
Dennis, John, B.Sc. (*Manchester*), Grad.I.C.E.
Derrick, Brian Frazer, B.C.E. (*Melbourne*), Stud.I.C.E.
Devine, Desmond Hylton, B.Sc. (*Cape Town*).
Dewhurst, Harry, B.Sc. (*Manchester*).
Dowling, John, B.Sc.(Eng.) (*London*).
Doyle, Geoffrey Colin, Grad.I.C.E.
Dutton, George Francis.
Earnshaw, Frank, Grad.I.C.E.
Eley, Brian James, B.Sc. (*Wales*), Grad.I.C.E.
Ellinger, John Henry, M.Sc.(Eng.) (*London*).
Elliott, John Cameron, B.Sc.(Eng.) (*London*).
Ellis, William Desmond, B.Sc. (*Belfast*).
Engels, Ernest Theodore, B.Sc. (*Witwatersrand*).
Epton, Henry Martin.
Facer, John Ramsden, B.Sc.Tech. (*Manchester*), Grad.I.C.E.

Finlay, Gordon Garvin, B.Sc. (*Belfast*), Grad.I.C.E.
Fish, Leonard Frederick, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Fleischmann-Allen, Richard Alexander, *D.S.C.*, B.Sc. (*Bristol*).
Forbes, Frank Gardiner, B.Sc. (*St. Andrews*).
Forde, George Robert Duncan, B.A., B.A.I. (*Dublin*).
Fulwood, Alan Frederick, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Gallagher, Edward Peter, M.Eng. (*Liverpool*).
Gardner, John David Walker, B.Sc. Tech. (*Manchester*), Grad.I.C.E.
Given, Alan Frederick Cranston, B.A., B.A.I. (*Dublin*).
Goodman, Joel, B.Sc. (*Witwatersrand*).
Gourley, Edward, B.Sc. (*Belfast*), Grad.I.C.E.
Graham, James Douglas, Grad.I.C.E.
Green, William Stanley.
Hall, Roland, Grad.I.C.E.
Hamer, John Carey, B.Sc. (*St Andrews*).
Hamilton, Allan Edward, B.Sc. (*Glasgow*).
Hanson, Douglas, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Harrison, John Douglas, B.Sc.(Eng.) (*London*).
Hay, *Major* John Duncan, B.Sc.(Eng.) (*London*), R.E.
Hayhurst, Harry, B.Sc.(Eng.) (*London*).
Henderson, Harry Westwood, Grad. I.C.E.
Henry, Samuel Alexander Campbell, B.A., B.A.I. (*Dublin*).
Hilton, Norman, Grad.I.C.E.
Hodgson, George Stubbs, B.Sc. (*St. Andrews*), Grad.I.C.E.
Howarth, Sydney.
Howe, Jack Clifford, B.Sc.(Eng.) (*London*).
Hunt, Harold Morley, B.Sc. (*Bristol*).
Hunter, Robert, Grad.I.C.E.
Hutchinson, Frederick George, B.Sc. (*Witwatersrand*).
Hyslop, David Robert Duncan.
Illston, John Michael, B.Sc.(Eng.) (*London*), Stud.I.C.E.
Jackson, Harold Lochner, B.Sc. (*Cape Town*).
Jackson, Robert Tyerman, Grad. I.C.E.
Jackson, Stuart, M.Sc.Tech. (*Manchester*).
James, Emlyn.
Jones, Arnold, Grad.I.C.E.
Jenkins, William Brynmor, B.Sc. (*Wales*).
Johnson, Leslie, B.Sc.(Eng.) (*London*).
Johnston, Frederick Gerald, B.Sc. (*Belfast*), Grad.I.C.E.
Jolly, Alwyn Grimshaw, B.Sc.(Eng.) (*London*).
Kane White, Anthony, B.C.E. (*Melbourne*).
Kennedy, Douglas Stewart.
Knott, Arthur Leslie, B.A., B.A.I. (*Dublin*), Grad.I.C.E.
Kruczala, Maksymilian Robert.
Kumarasuriar, Chelliah, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Lancaster, Michael Ralph, B.E. (*New Zealand*).
Langan, John James, B.Eng. (*Liverpool*), Grad.I.C.E.
Larkman, David Francis George.
Lawrence, Edwin Derek, B.Sc.(Eng.) (*London*).
Leaman, William John, B.Sc. (*Bristol*), Grad.I.C.E.
Leech, William Murray.
Leighton, David Hay, B.Sc. (*St Andrews*).
Leitch, Robert John Stuart, B.Sc. (*Glasgow*), Grad.I.C.E.
Lethbridge, John Harold, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Lidstone, Samuel George David, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Liszka, Stanislaw Kazimierz.
Llewellyn, Trevor John, B.Sc. (*Durham*).
Lucas, Cedric John, B.Sc.(Eng.) (*London*).
Lye, Baba Royston Xiwar, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Lynch, James Cyril.
MacDonald, John Moorhead, B.Sc. (*Belfast*).
Mackenzie, Kenneth, B.Sc. (*Edinburgh*), Grad.I.C.E.
McCreery, Thomas Ian, B.E. (*Western Australia*).
McGlashan, Trevor Bain, B.E. (*New Zealand*).
McLean, Daniel, B.Sc. (*Glasgow*), Grad.I.C.E.
McManus, Edmund Wilfred, B.Sc. (*Belfast*).
Malham, John Frederick.
Mann, Christopher Roderick, Stud. I.C.E.
Margolis, Solomon David, B.Sc. (*Cape Town*), Grad.I.C.E.
Marshall, James.
Marshall, Ralph, B.Sc. (*Bristol*).
Maufe, Gabriel Gordon, *M.C.*, B.Sc. (Eng.) (*London*).

Megit, John Sydney Charles, B.Sc. (Eng.) (*London*), Grad.I.C.E.

Mendis, Manemeldura Charles Bernard, B.Sc.(Eng.) (*London*).

Merry, Geoffrey Beaumont.

Millar, William Davidson, B.Sc. (*Aberdeen*).

Miller, Michael Jenner, B.Sc. (*Birmingham*).

Montgomery, *Major* John Coutts Duffus, B.A. (*Cantab.*), R.E.

Morris, Robert William, M.A. (*Cantab.*), Grad.I.C.E.

Nabi, Jamil Abdul, M.Sc.(Eng.) (*London*), Grad.I.C.E.

Nicholas, John, B.Sc. (*Birmingham*), Grad.I.C.E.

Nosek, Antoni, B.Sc.(Eng.) (*London*).

O'Maolain, Padraig Seosaim, B.E. (*National*).

Ormerod, Derek, B.Sc.Tech. (*Manchester*), Grad.I.C.E.

Owens, Owen, B.Sc. (*Witwatersrand*).

Paterson, Ian Russell Cameron, B.Sc. (*Edinburgh*).

Payn, Keith, B.Sc. (*South Africa*).

Pearce, Roger Le Blond, B.Sc. (Eng.) (*London*), Grad.I.C.E.

Pendry, John, B.Sc. (*Belfast*).

Perkins, Edward Julian Churchill, B.Sc. (*Witwatersrand*).

Poole, Leslie Frederick, Grad.I.C.E.

Pryor, Robert Nelson, B.Sc.(Eng.) (*London*).

Pullinger, John Sturt, B.Sc. (*Birmingham*).

Pursey, Guy Desmond George.

Rabling, Frank Kenneth, B.C.E. (*Melbourne*).

Radecki, Stanislaw Jan, B.Sc.(Eng.) (*London*).

Ramsay, James Wallace, B.Sc. (*Durham*).

Rees, Norman Griffiths, B.Eng. (*Liverpool*), Grad.I.C.E.

Rhodes, John Henry, B.Sc. (*Birmingham*).

Robertson, George Webster, B.Sc. (*Aberdeen*), Grad.I.C.E.

Robson, Dennis Bungard, B.Eng. (*Liverpool*).

Rule, Stanley Noel.

Saunders, Roland William, B.A. (*Cantab.*).

Saxton, Kenneth John Harley, B.A. (*Cantab.*), Grad.I.C.E.

Scallan, Ernest Reginald, B.E., B.Sc. (*National*).

Seabrook, Brian John, B.Sc.(Eng.) (*London*), Stud.I.C.E.

Sephton, Edgar Pote, B.Sc. (*Cape Town*).

Shedden, James Auld, B.Sc. (*Glasgow*), Grad.I.C.E.

Shiels, Joseph Sylvan, B.Sc. (*Belfast*), Grad.I.C.E.

Shipway, James Simpson, B.Sc. (*Glasgow*), Grad.I.C.E.

Simms, Terence James Gillespie, B.Sc. (*Belfast*), Grad.I.C.E.

Skinner, Richard Newlyn, B.Sc. (Eng.) (*London*), Grad.I.C.E.

Smedley, Granville Barrie, B.Sc. Tech. (*Manchester*), Grad.I.C.E.

Smith, George Arthur.

Sorber, Jan Hendrik Christiaan.

Steane, Ernest John Douglas, B.E. (*Tasmania*).

Stoker, Terence Alexander, B.Eng. (*Liverpool*), Grad.I.C.E.

Stott, Donald, B.Eng. (*Liverpool*).

Streeter, Henry William, B.Sc. (*Witwatersrand*).

Tait, Mostyn Brownlow, B.E. (*New Zealand*), Stud.I.C.E.

Tate, Alan George, B.Sc.(Eng.) (*London*), Grad.I.C.E.

Taylor, Leonard Edwin, B.Sc.(Eng.) (*London*), Grad.I.C.E.

Taylor, Robert White, B.Sc. (*Glasgow*), Grad.I.C.E.

Thilaganathan, Kanapathipillai, B.Sc.(Eng.) (*London*), Grad.I.C.E.

Thorp, John, Grad.I.C.E.

Thwaites, Charles Alexander, *D.S.C.*, B.Sc. (*Durham*).

Townsend, Arthur George, B.Sc. (*Belfast*), Grad.I.C.E.

Turnbull, Thomas Donaldson.

Turner, Peter Maurice, B.Sc.(Eng.) (*London*), Grad.I.C.E.

Turney, William McDonald Noble, B.A. (*Cantab.*).

van Ameróngen, Carel.

Vaughan, John Henry Vaughan, B.A. (*Cantab.*).

Walters, Sidney George, Grad.I.C.E.

Ward, Alfred Neville, B.Sc.(Eng.) (*London*), Grad.I.C.E.

Ware, Peter Herbert, Grad.I.C.E.

Weatherseed, Ian Alexander, B.Sc. (Eng.) (*London*).

Webster, Keith Coverdale, Grad. I.C.E.

White, Keith Edward Marcus, Grad. I.C.E.

Wilkinson, Harold William, M.A. (*Cantab.*).

Williams, Basil Patrick, B.Sc. (*Bristol*).

Williams, Harold.

Wilson, Philip Healy.

Wilson, William Wallace, B.Sc. (*South Africa*).

Woodford, Anthony John, B.Sc. (Eng.) (*London*), Grad.I.C.E.

DEATHS

It is with deep regret that intimation of the following deaths has been received.

Members

John Dekeyne Atkinson, B.A. (E. 1922, T. 1935).
Alfred Thomas Best (E. 1904, T. 1931).
William Eames Caton (E. 1927).
Wilfrid Dinsey Chapman, M.C.E. (E. 1932, T. 1941).
Sir (**Frederick Leighton**) **Victor Mills**, Bart. (E. 1934, T. 1944).
John Orr, O.B.E., LL.D., B.Sc. (E. 1904, T. 1910).
Charles Herbert Rutter (E. 1894, T. 1913).
William Storrie (E. 1909, T. 1929).
John Sigismund Wilson (E. 1903, T. 1927).
Sir **Cyril Roe Muston Young**, Bart. (E. 1912, T. 1929).

Associate Members

Harry Bertram Edwin Brown (E. 1910).
Major **Douglas Marshall Cannon**, M.B.E., R.E.M.E. (E. 1932).
Arthur Henry Clarke, B.Sc. (E. 1936).
John Frederick Cubbon, M.C., D.S.O. (E. 1942).
Albert Edward Dicks (E. 1910).
Frederick George Helsby (E. 1910).
Jack Holt (E. 1928).
William Henry Maxwell (E. 1900).
Alfred John Adams Roseveare, B.Sc.(Eng.) (E. 1945).
Harry Lionel Sargent (E. 1895).

Graduate

Eric Hedley Kerry, B.Sc. (A. 1952).

Student

Michael Oliver Rogers (A. 1947).

OBITUARY

Sir ERNEST ALBERT SEYMOUR BELL, C.I.E., F.C.H., who died at his home in London on the 8th January, 1955, was born on the 1st September, 1867.

He received his engineering training at the Royal Indian Engineering College, Coopers Hill, and entered the railway branch of the Indian Public Works Department in 1888 as an Assistant Engineer. After being employed on the construction of the East Coast Railway from 1889 to 1894, he joined the Assam–Bengal Railway in an administrative capacity. He served with the Government of India Railway Secretariat from 1902 until 1905, and built the Nagda–Muttra line between Bombay and Delhi.

During the first World War he was a member of the Government Commission to Mesopotamia, investigating railway problems in that area. After the war he was appointed Agent (a post now known as General Manager) of his old railway—the East Bengal Railway—at Calcutta and later of the North-Western Railway at Lahore.

After filling several executive and engineering posts Sir Ernest was appointed, in 1920, a member of the Railway Board of the Government of India. He was created a Companion of the Indian Empire in 1919.

He left India in 1923 to become the Government Director of Indian Railways in London. In that year he was made a Knight Bachelor.

After retiring from Government service in 1926 he became Chairman and Managing Director of the South Indian Railway Company and was Chairman of the Barsi Light Railway until 1951.

Sir Ernest was elected an Associate Member of the Institution in 1895, and was transferred to the class of Members in 1913. He was a Member of Council in 1919.

In 1902 he married Miss A. B. Loynes, and there were three sons and one daughter. She died in 1941, and 2 years later he married Miss Lena Jones, who survives him.

CORRIGENDA

Proceedings, Part I, July 1955.

p. 472, in the Authors' names, *for* Past-President I.C.E. *read* Past-President I.E.E.

p. 490, section 6.1, para. 3, line 5, *for* annual *read* annular.

p. 638, para. 6, line 6, *for* technical *read* protective.

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